Title: Foundations of Quantum Mechanics #1

Date: Jan 08, 2008 06:30 PM

URL: http://pirsa.org/08010017

Abstract: Interferometry, measurement and interpretation. Beyond the quanta.

Introduction to the Foundations of Quantum Theory

- *Why* the quanta? How do we make sense of the occurrence of quantum phenomena?
  - What are the properties of a phenomena that makes it quantum?
  - What kind of physical process can possibly account for such properties?
  - How does the everyday classical world co-exist with quantum phenomena?
  - ...and could it be different?
- With conceptual *clarity* and *precision*!

Introduction to the Foundations of Quantum Theory

- *Why* the quanta? How do we make sense of the occurrence of quantum phenomena?
  - What are the properties of a phenomena that makes it quantum?
  - What kind of physical process can possibly account for such properties?
  - How does the everyday classical world co-exist with quantum phenomena?
  - ...and could it be different?
- With conceptual *clarity* and *precision*!

Introduction to the Foundations of Quantum Theory

- Lecture 1: Quantum phenomena.
  - Just what makes a quantum thing, quantum? An examination of interferometry experiments.
- Lecture 2: Measurement and interpretation
  - What is the measurement problem? Should we be worried?
- Lecture 3: EPR, Bell and quantum non-locality
  - Is there a conflict between relativity and quantum theory?
- Lecture 4: Beyond the quantum
  - Can we catch a glimpse of the theories that might, one day, replace quantum theory?

Quantum phenomena : interferometry

Introduction to the Foundations of Quantum Theory

- Lecture 1: Quantum phenomena.
  - Just what makes a quantum thing, quantum? An examination of interferometry experiments.
- Lecture 2: Measurement and interpretation
  - What is the measurement problem? Should we be worried?
- Lecture 3: EPR, Bell and quantum non-locality
  - Is there a conflict between relativity and quantum theory?
- Lecture 4: Beyond the quantum
  - Can we catch a glimpse of the theories that might, one day, replace quantum theory?

www.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundamental Physics/

$\psi(x)$

$P(x)$

www.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundamental_Physics/

$\psi(x)$

$P(x) =$

www.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundamental_Physics/

$\psi(x)$

$P(x) = |\psi(x)|^2 dx$

www.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundamental_Physics/

$\psi(x)$

$P(x) = |\psi(x)|^2 dx$

www.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundamental_Physics/

$\psi(x)$

$P(x) = |\psi(x)|^2 dx$

$\int P(x)\,dx$

www.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundamental_Physics/

$\psi(x)$

$P(x) = |\psi(x)|^2 dx$

$\int P(x)\,dx =$

$$\psi(x)$$

$$P(x) = |\psi(x)|^2 dx$$

$$\int P(x)\,dx = 1$$

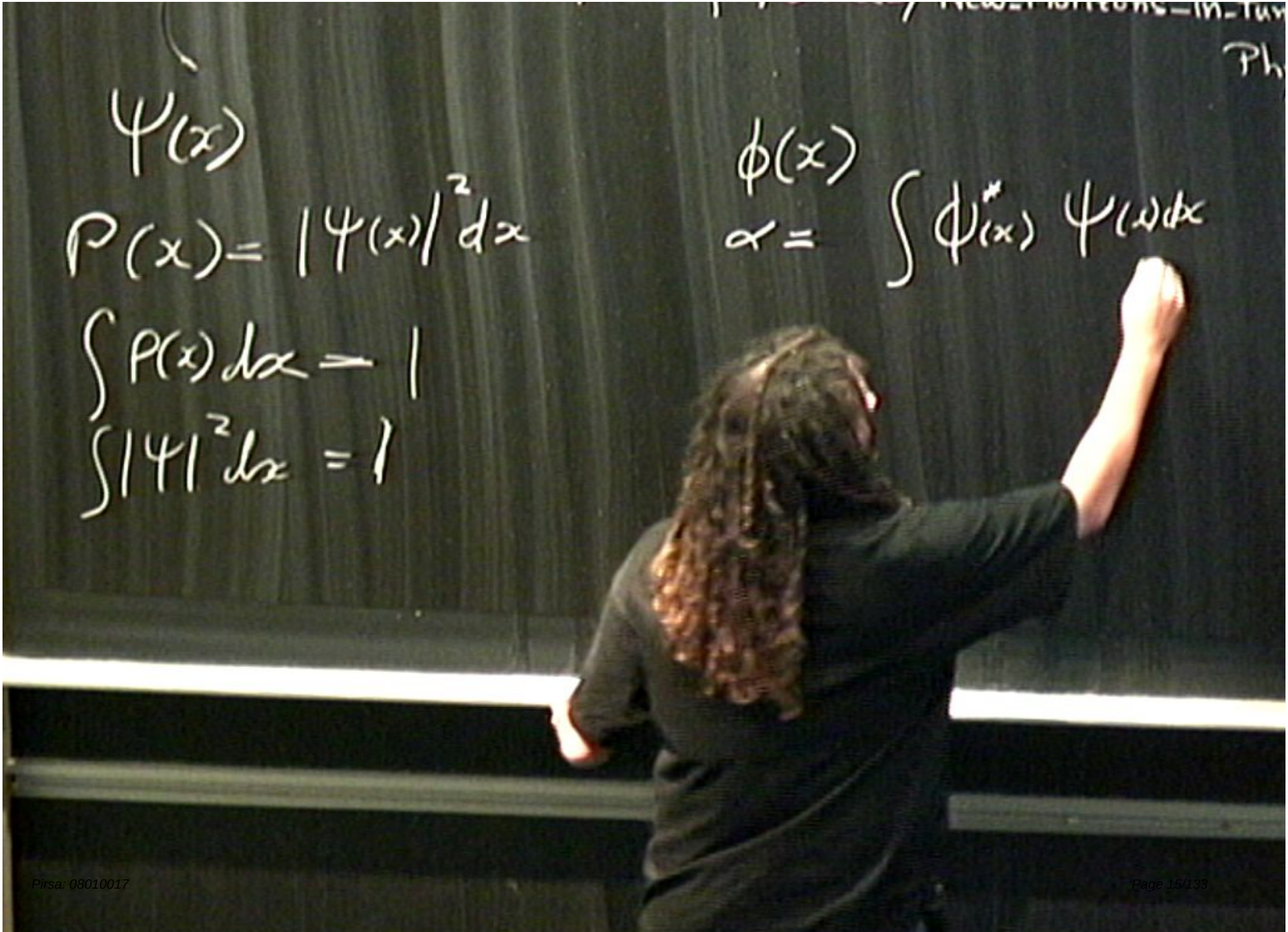
$$\int |\psi|^2 dx = 1$$

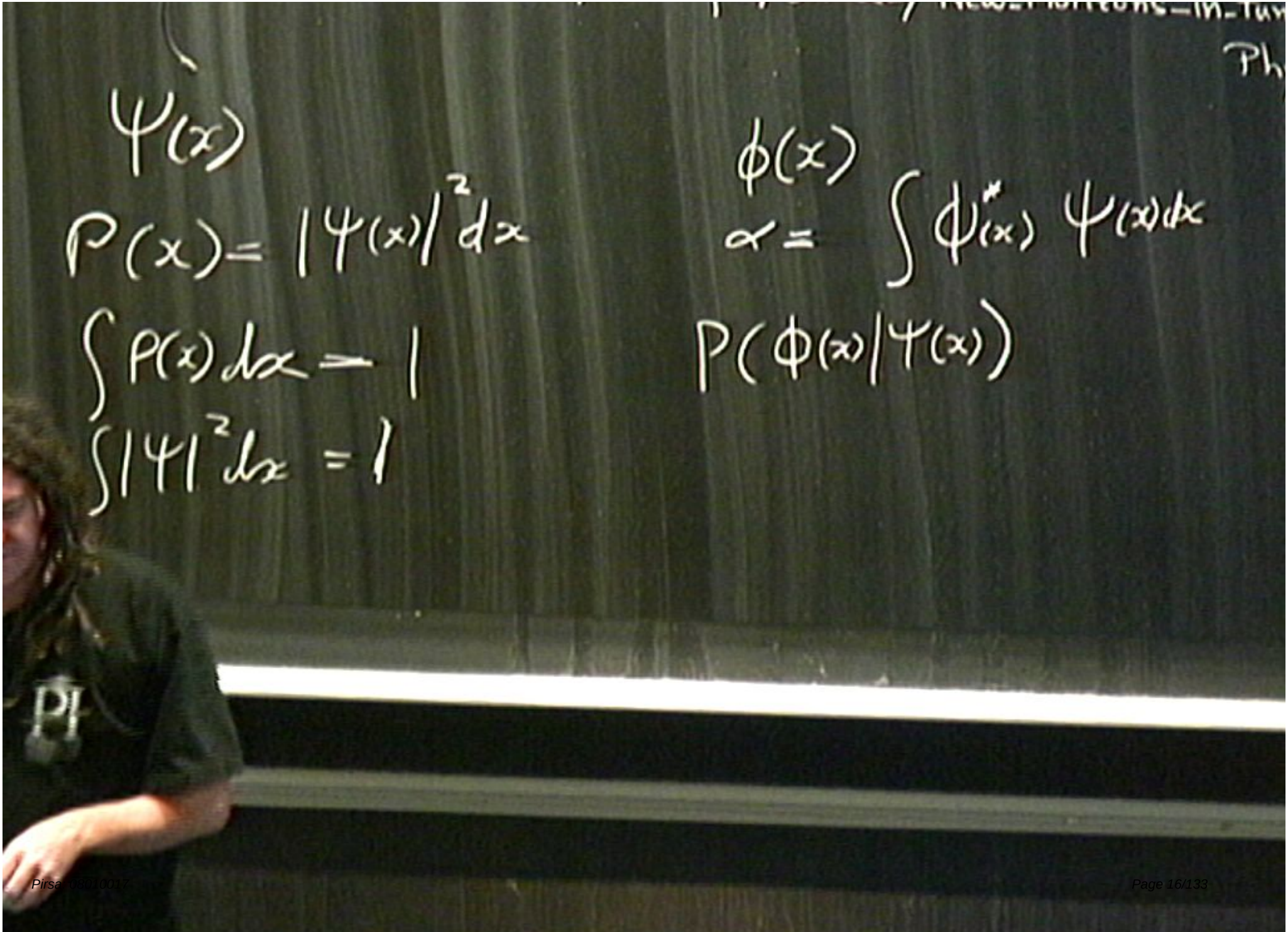
$\psi(x)$ $\phi(x)$

$P(x) = |\psi(x)|^2 dx$

$\int P(x)\,dx = 1$

$\int |\psi|^2 dx = 1$


$\psi(x)$
$P(x) = |\psi(x)|^2 dx$
$\int P(x)\,dx = 1$
$\int |\psi|^2 dx = 1$
$\phi(x)$
$\alpha = \int \phi^*(x)\,\psi(x)\,dx$


$\psi(x)$
$P(x) = |\psi(x)|^2 dx$
$\int P(x)\,dx = 1$
$\int |\psi|^2 dx = 1$
$\phi(x)$
$\alpha = \int \phi^*(x)\,\psi(x)\,dx$
$P(\phi(x)|\psi(x))$

$\psi(x)$

$P(x) = |\psi(x)|^2 dx$

$\int P(x)\,dx = 1$

$\int |\psi|^2 dx = 1$

$\phi(x)$

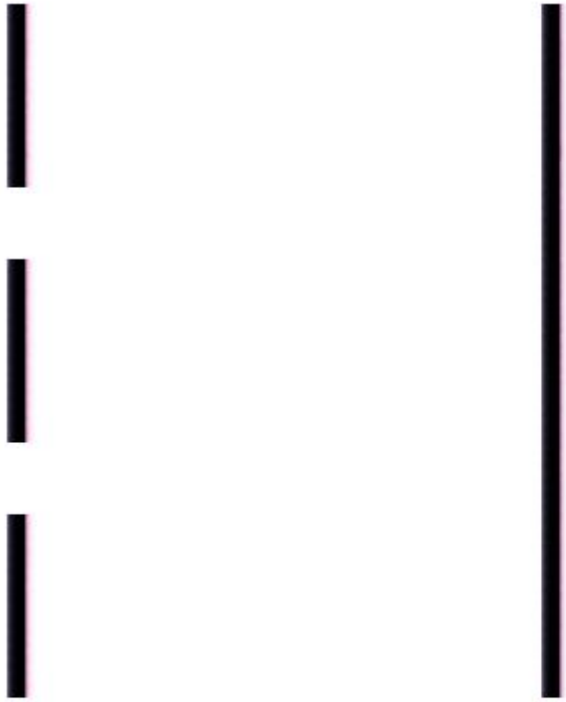
$\alpha = \int \phi^*(x)\,\psi(x)\,dx$

$P(\phi(x)|\psi(x)) = |\alpha|^2$

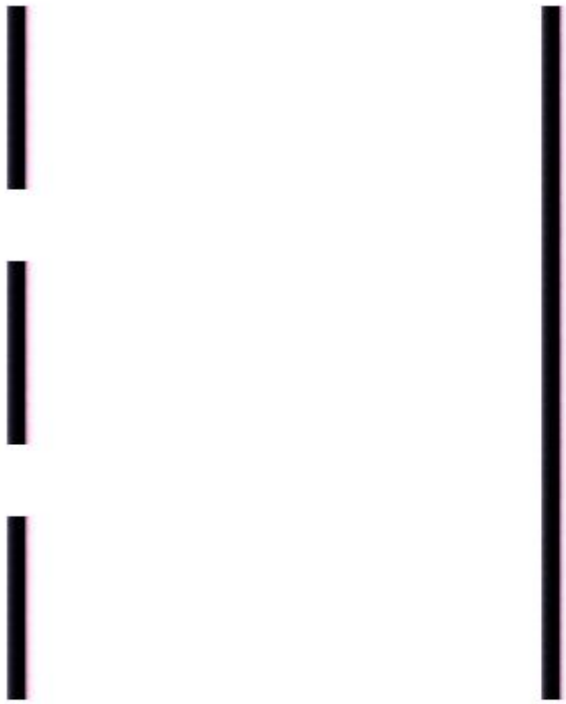
Introduction to the Foundations of Quantum Theory

- Lecture 1: Quantum phenomena.
  - Just what makes a quantum thing, quantum? An examination of interferometry experiments.
- Lecture 2: Measurement and interpretation
  - What is the measurement problem? Should we be worried?
- Lecture 3: EPR, Bell and quantum non-locality
  - Is there a conflict between relativity and quantum theory?
- Lecture 4: Beyond the quantum
  - Can we catch a glimpse of the theories that might, one day, replace quantum theory?

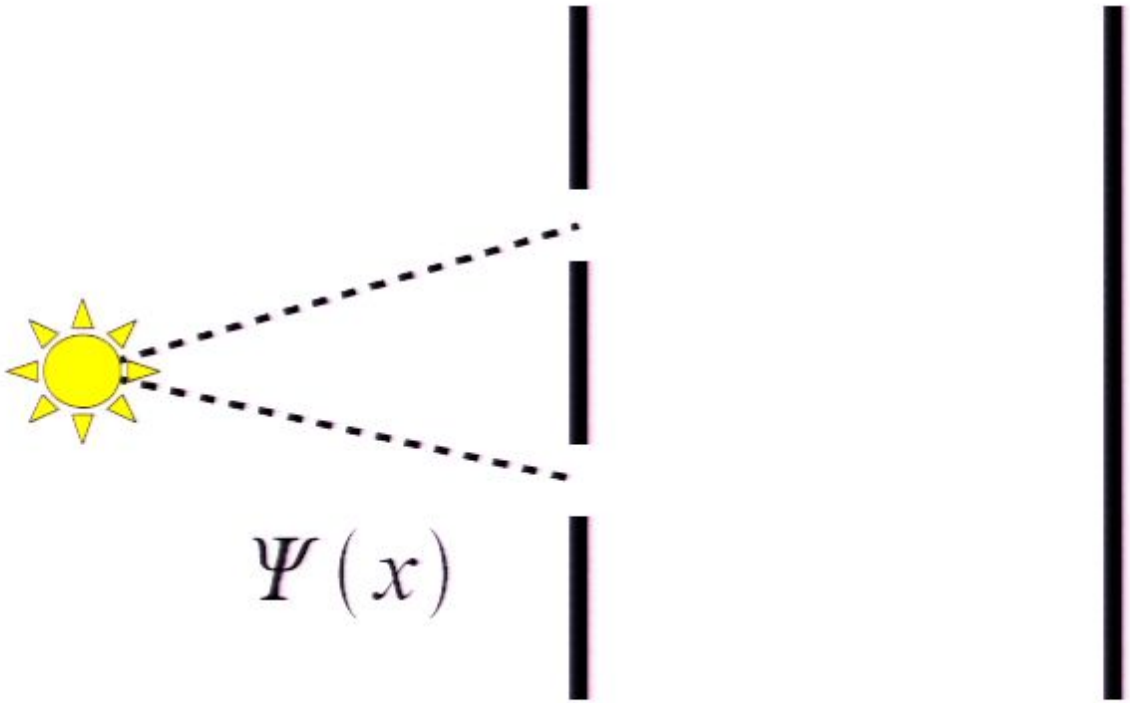
Quantum phenomena : interferometry



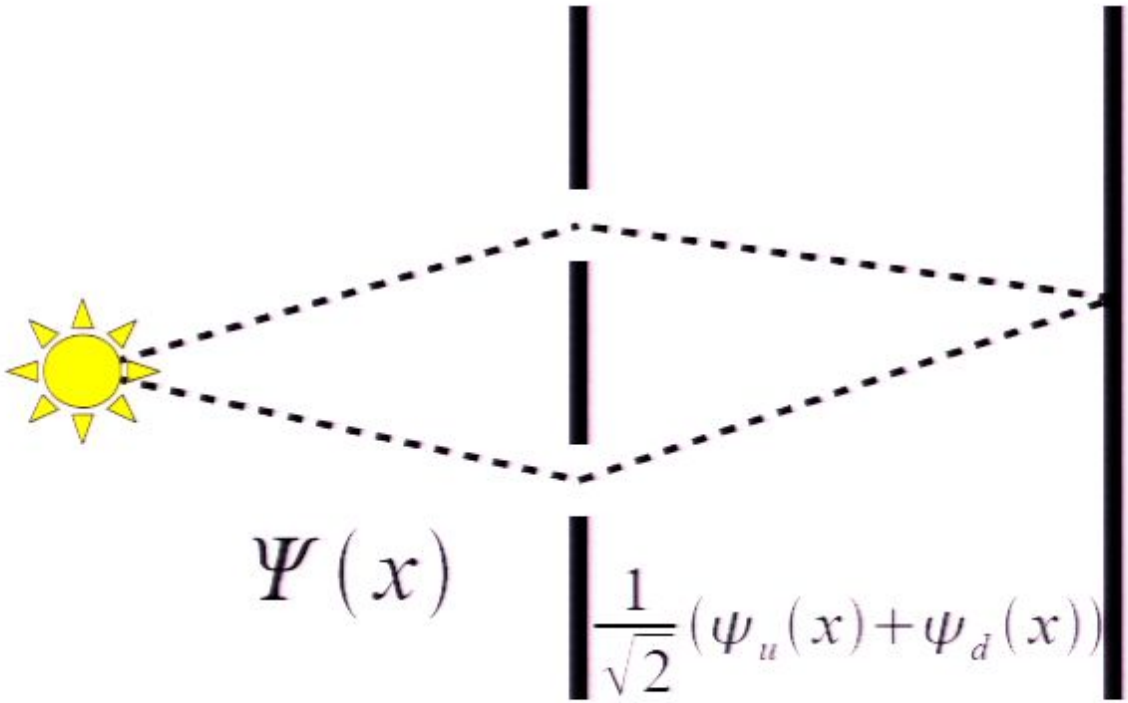
Quantum phenomena : interferometry



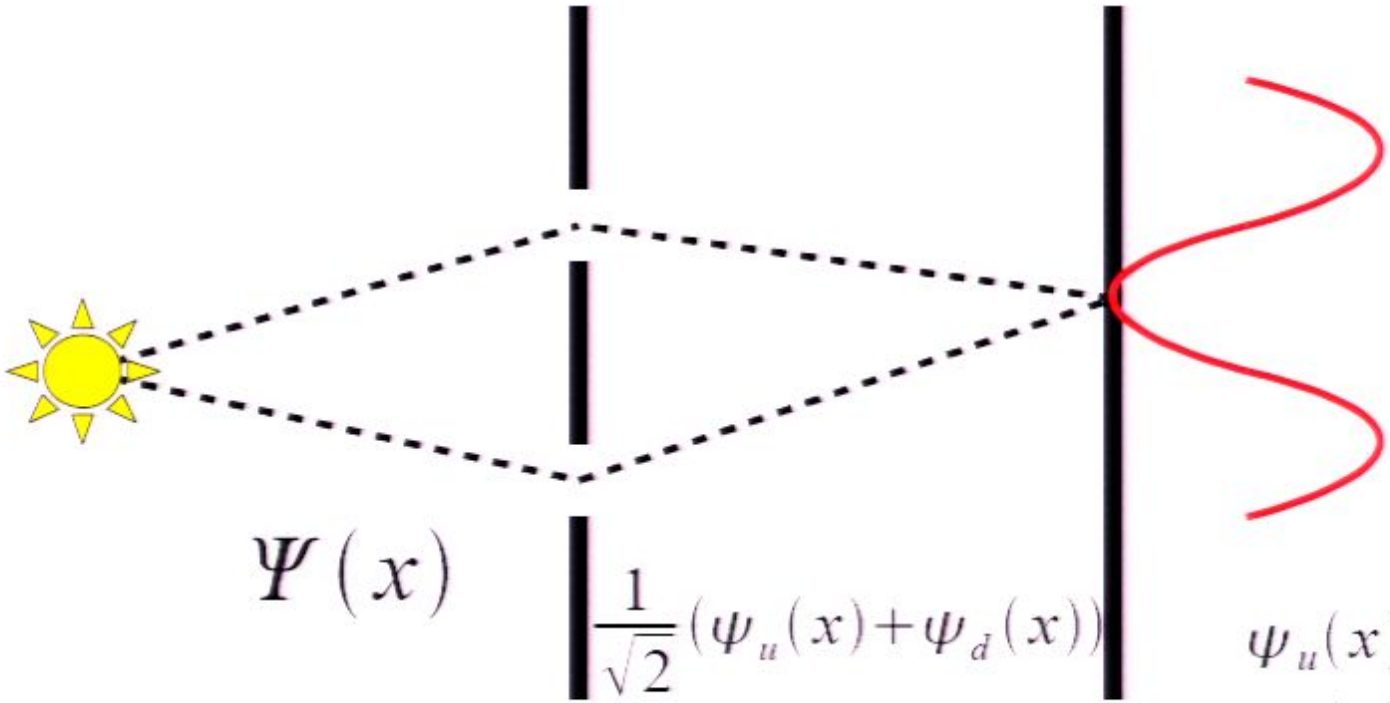
Quantum phenomena : interferometry



Quantum phenomena : interferometry



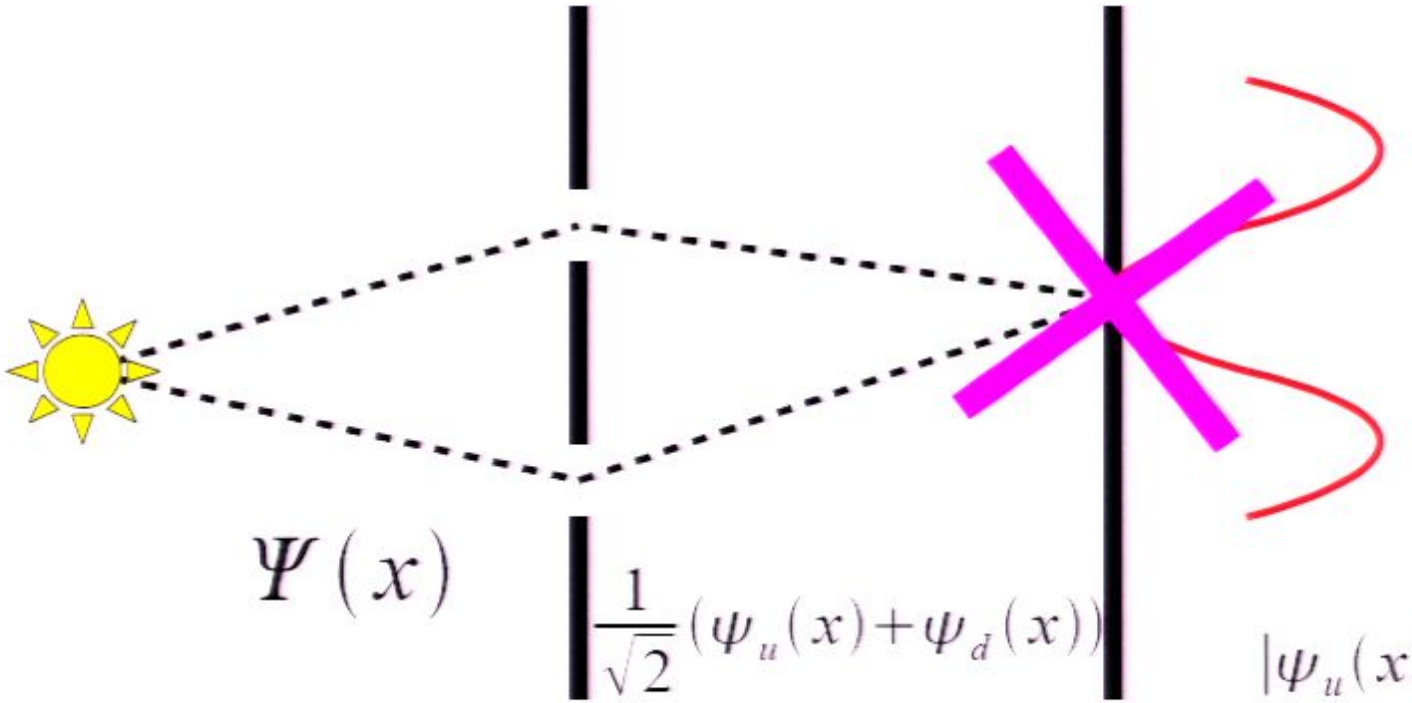
Quantum phenomena : interferometry



$$\psi_u(x)=|\psi_u(x)|e^{iS_u(x)}$$
$$\psi_d(x)=|\psi_d(x)|e^{iS_d(x)}$$

$$P(x)=\Psi^*(x)\Psi(x)=\frac{1}{2}\left(|\psi_u(x)|^2+|\psi_d(x)|^2+2|\psi_u(x)||\psi_d(x)|\cos(S_u(x)-S_d(x))\right)$$

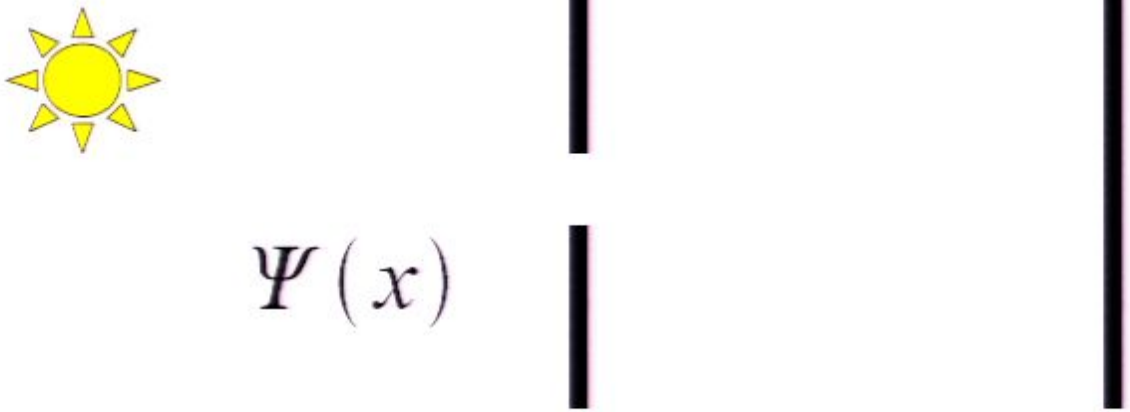
Quantum phenomena : interferometry



$$|\psi_u(x)|=|\psi_d(x)|$$
$$S_u(x)-S_d(x)=\pi+2\pi n$$

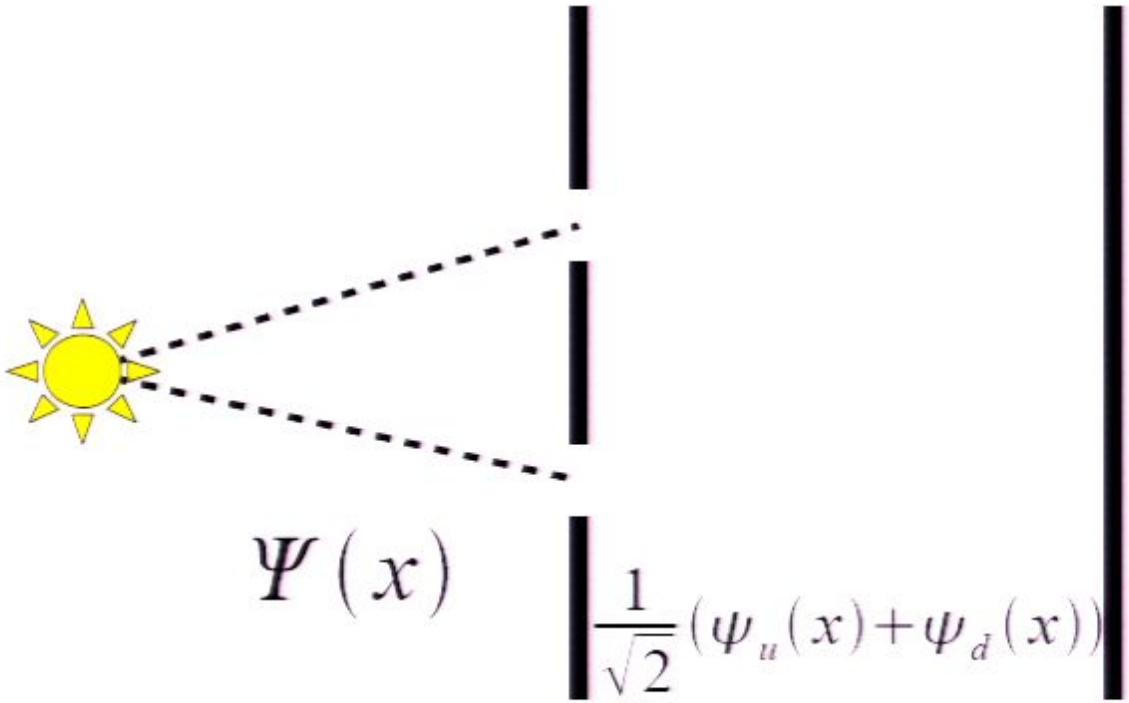
$$P(x)=\Psi^*(x)\Psi(x)=\frac{1}{2}\left(|\psi_u(x)|^2+|\psi_d(x)|^2+2|\psi_u(x)||\psi_d(x)|\cos(S_u(x)-S_d(x))\right)$$

Quantum phenomena : interferometry

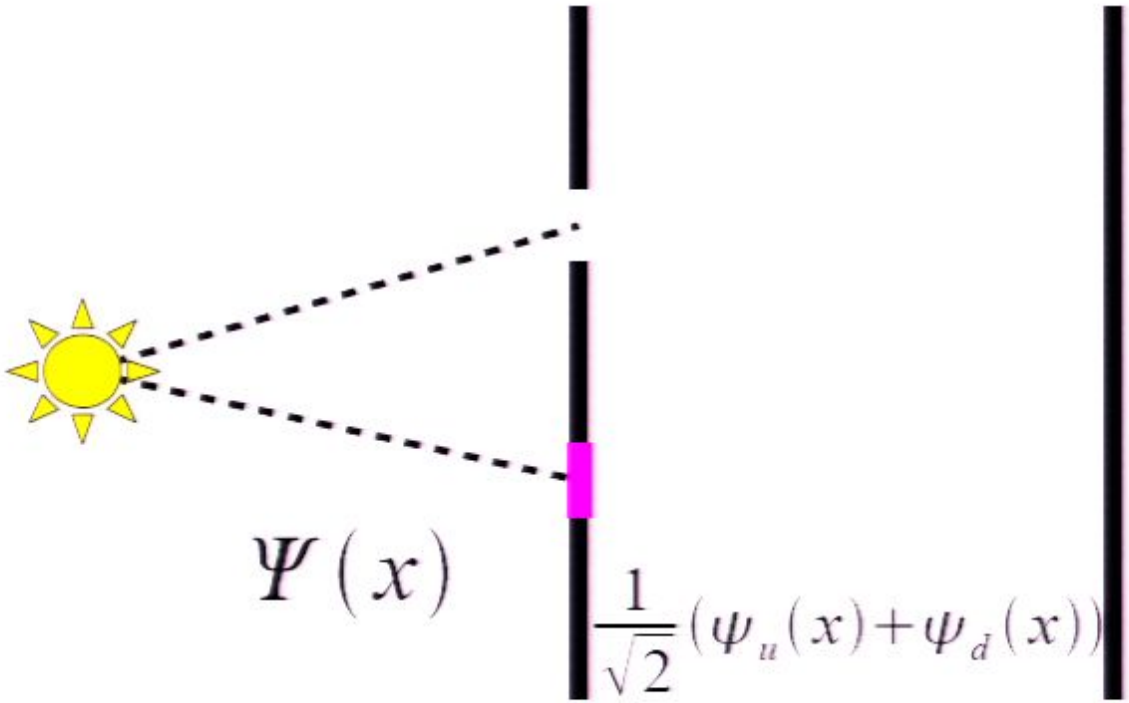


Is $|\Psi(x)|^2$ the probability of the photon *being* at "x",
or is it just the probability of *finding* the photon at "x",
if one chooses to look for it?
(If the latter, what is the photon doing if no-one is looking?)

Quantum phenomena : interferometry

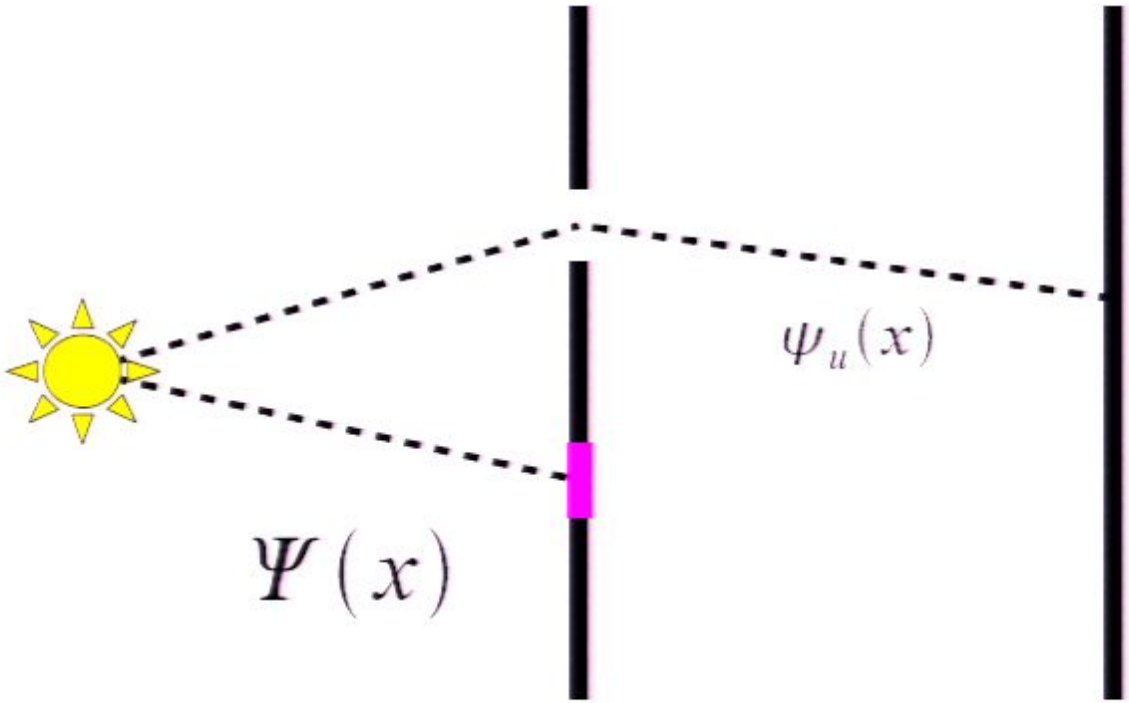


Quantum phenomena : interferometry



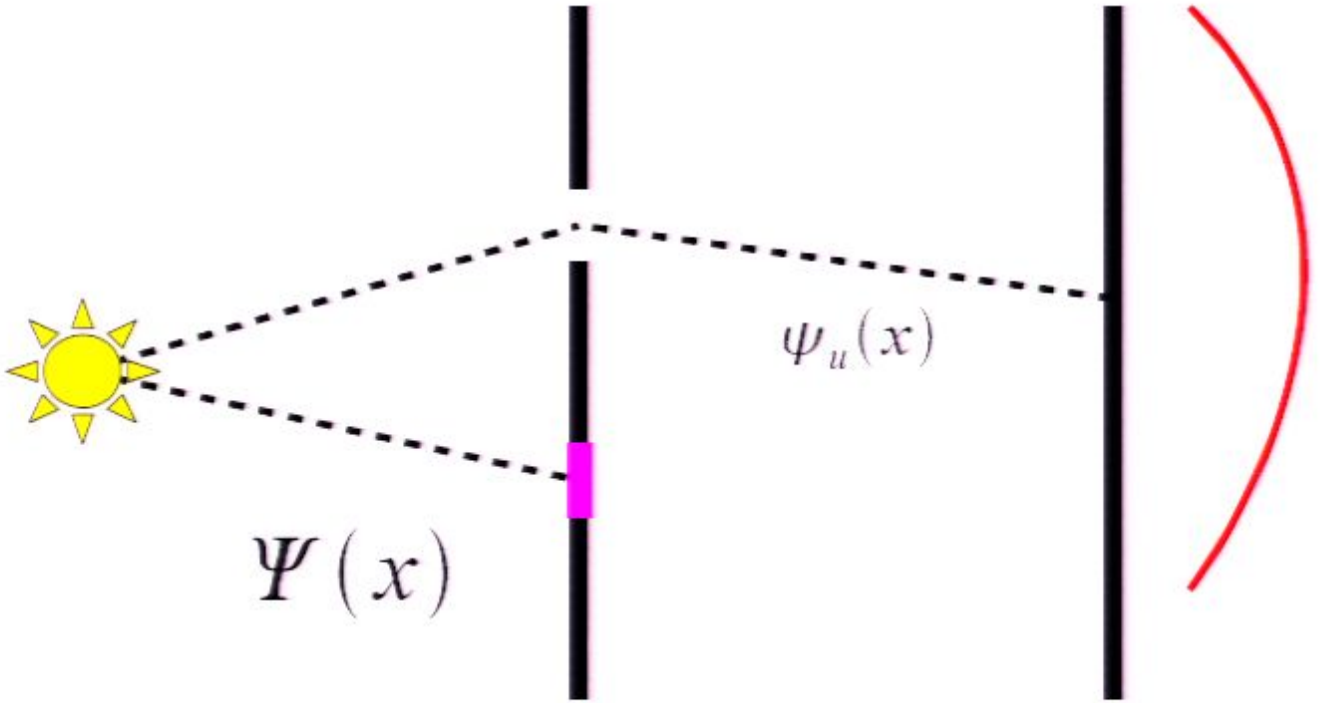
$$P(d)=\left|\int \psi_d{}^*(x)\,\Psi(x)\,dx\right|^2=\frac{1}{2}$$

Quantum phenomena : interferometry



$$P(u) = \left| \int \psi_u^*(x) \Psi(x)\, dx \right|^2 = \frac{1}{2}$$

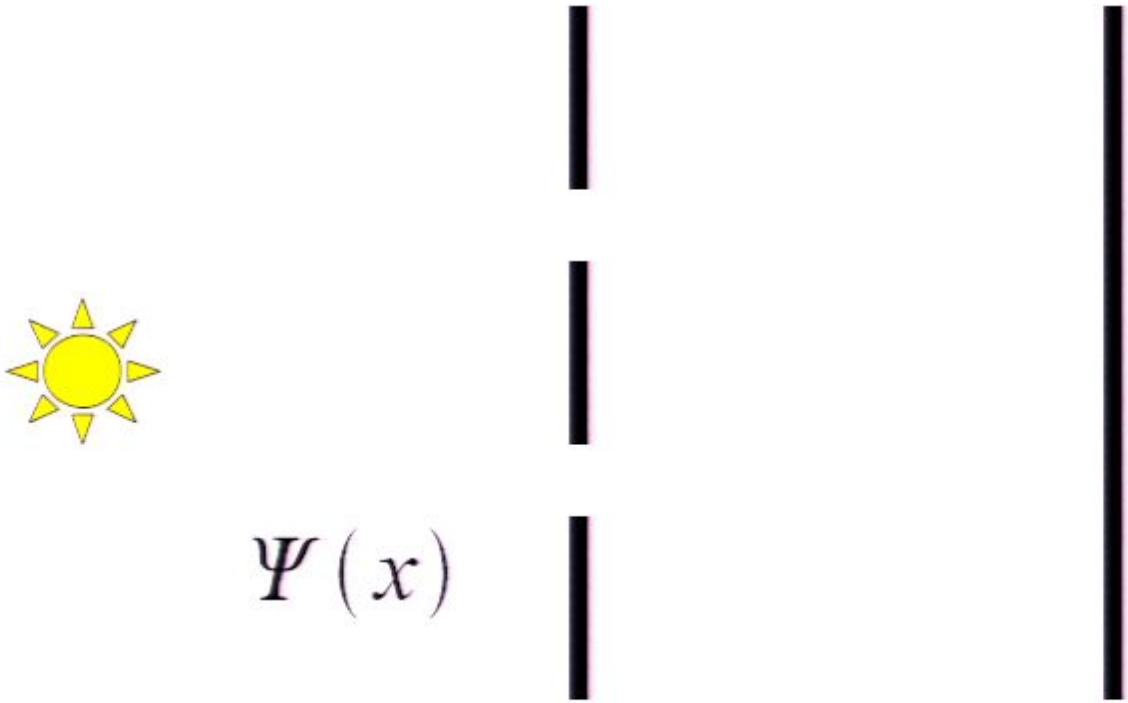
Quantum phenomena : interferometry



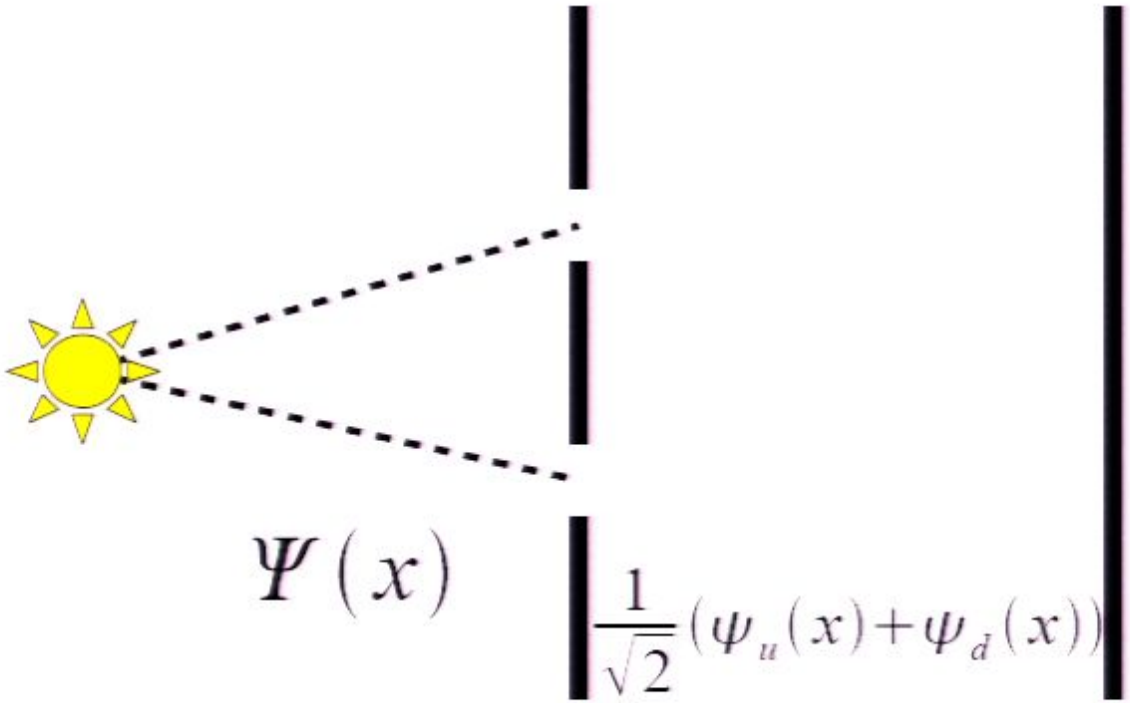
$$P(x|u)=|\psi_u(x)|^2$$

$$\psi_u(x)=|\psi_u(x)|e^{iS_u(x)}$$

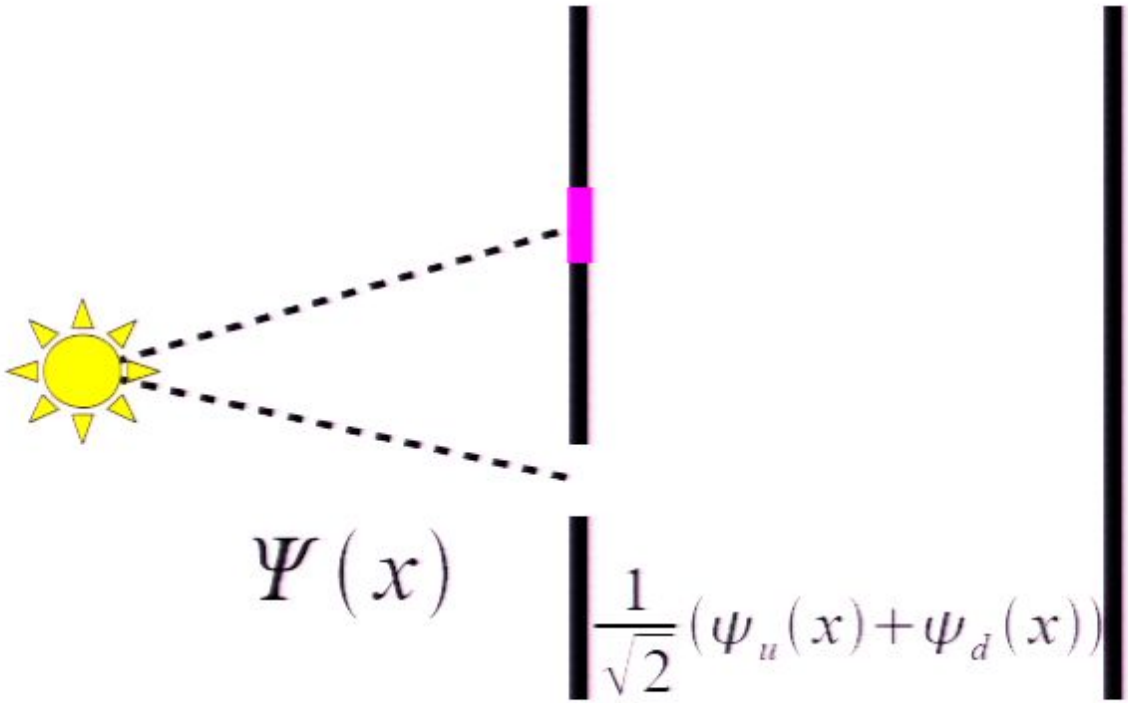
Quantum phenomena : interferometry



Quantum phenomena : interferometry

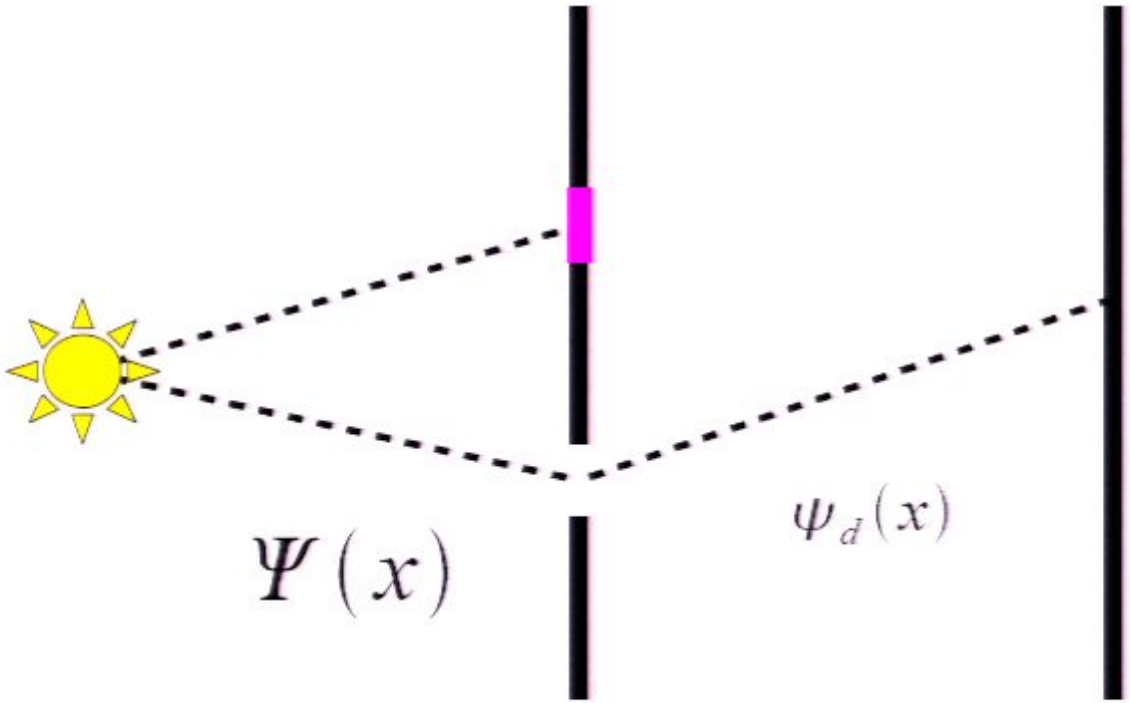


Quantum phenomena : interferometry



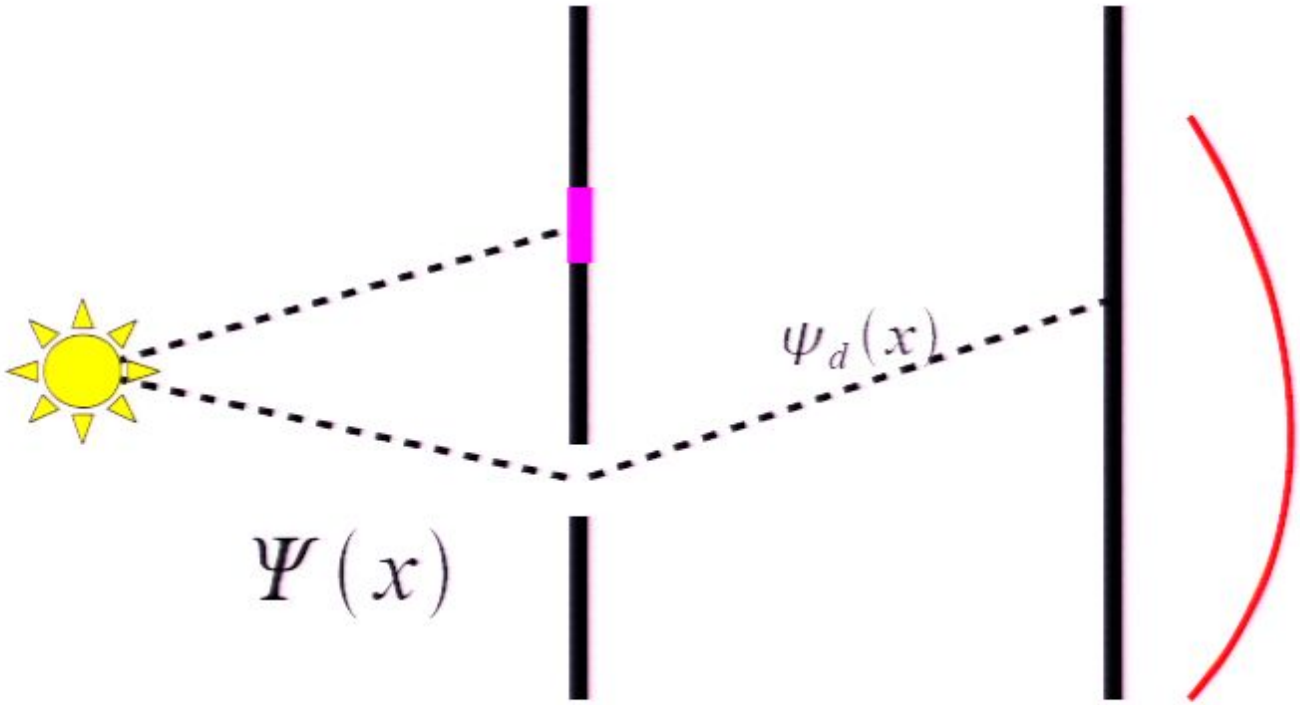
$$P(u)=\left|\int \psi_u^*(x)\Psi(x)\,dx\right|^2=\frac{1}{2}$$

Quantum phenomena : interferometry



$$P(d) = \left| \int \psi_d^*(x)\, \Psi(x)\, dx \right|^2 = \frac{1}{2}$$

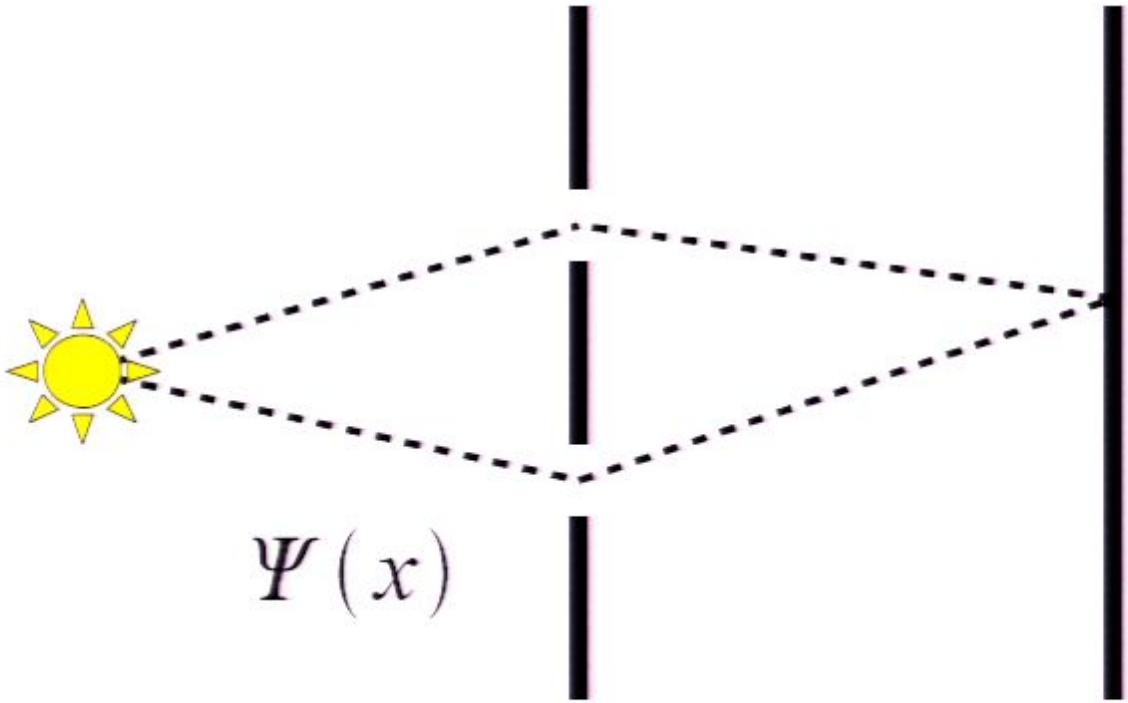
Quantum phenomena : interferometry



$$P(x|d) = |\psi_d(x)|$$

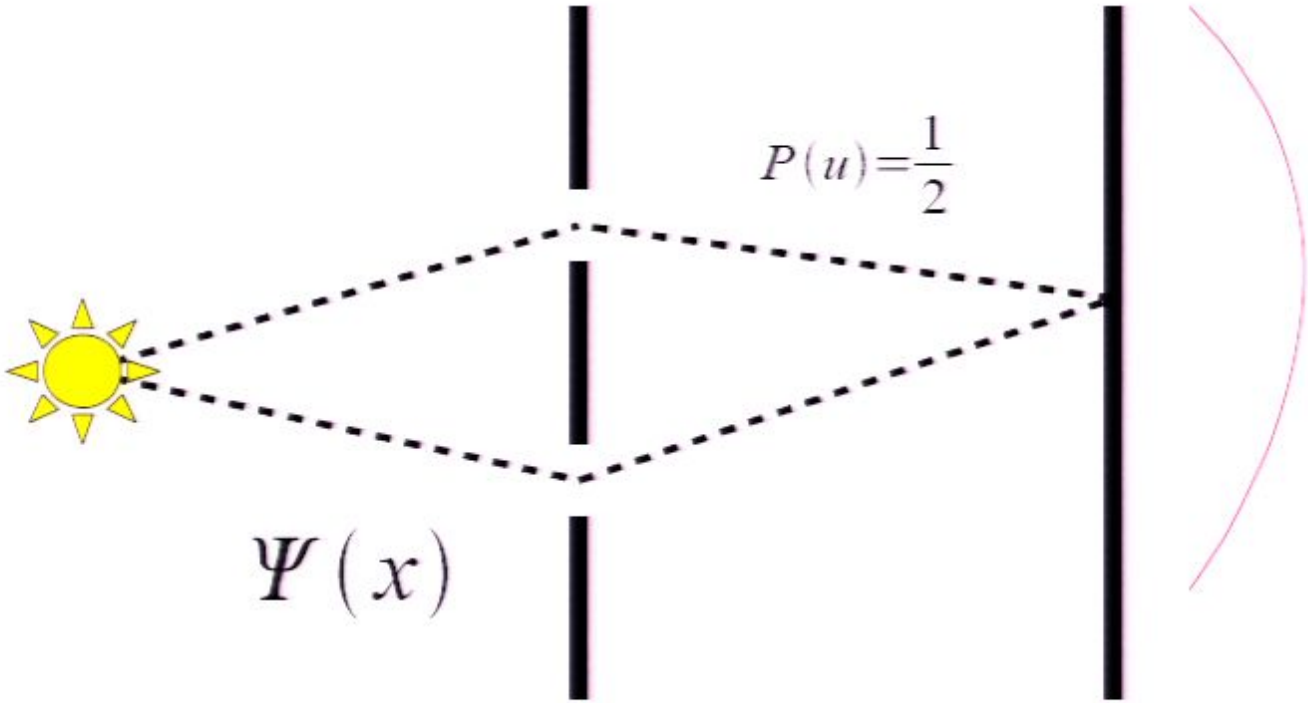
$$\psi_d(x) = |\psi_d(x)| e^{iS_d(x)}$$

Quantum phenomena : interferometry



$$\psi_u(x) = |\psi_u(x)| e^{iS_u(x}$$
$$\psi_d(x) = |\psi_d(x)| e^{iS_d(x}$$

Quantum phenomena : interferometry

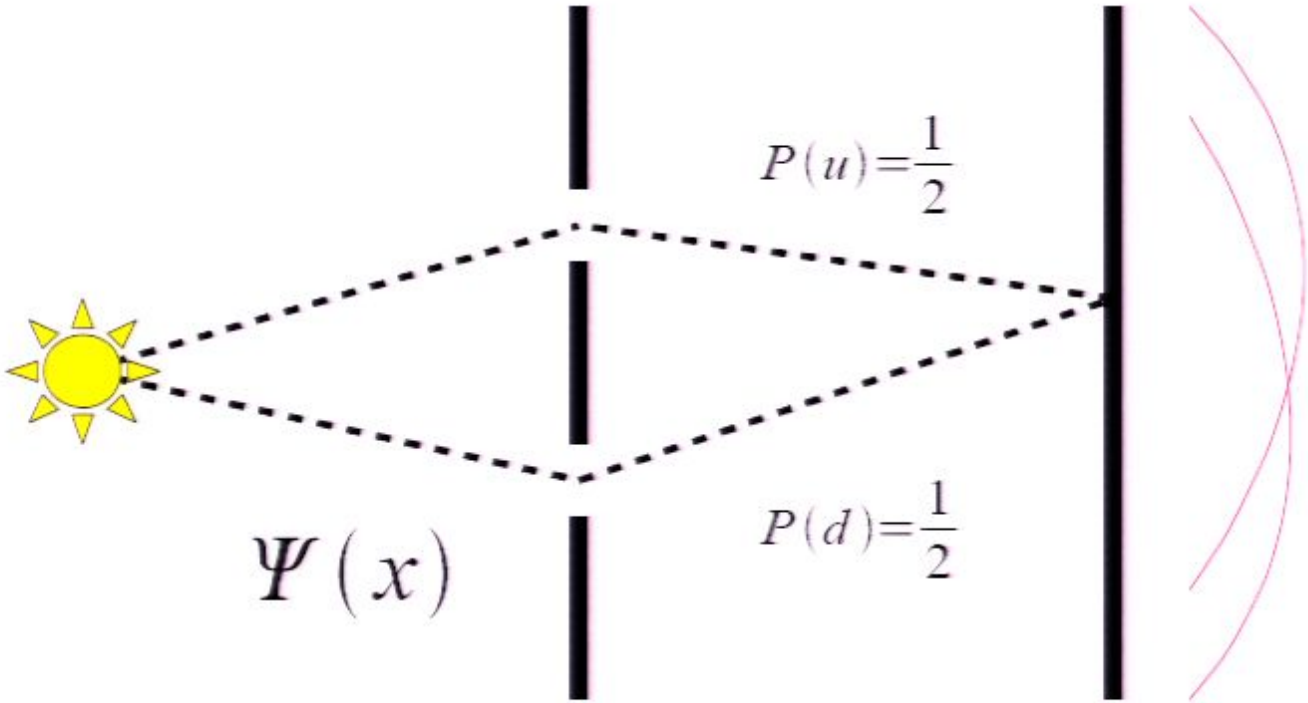


$$P(x|u)=|\psi_u(x)|^2$$

$$\psi_u(x)=|\psi_u(x)|e^{iS_u(x}$$

$$\psi_d(x)=|\psi_d(x)|e^{iS_d(x}$$

Quantum phenomena : interferometry



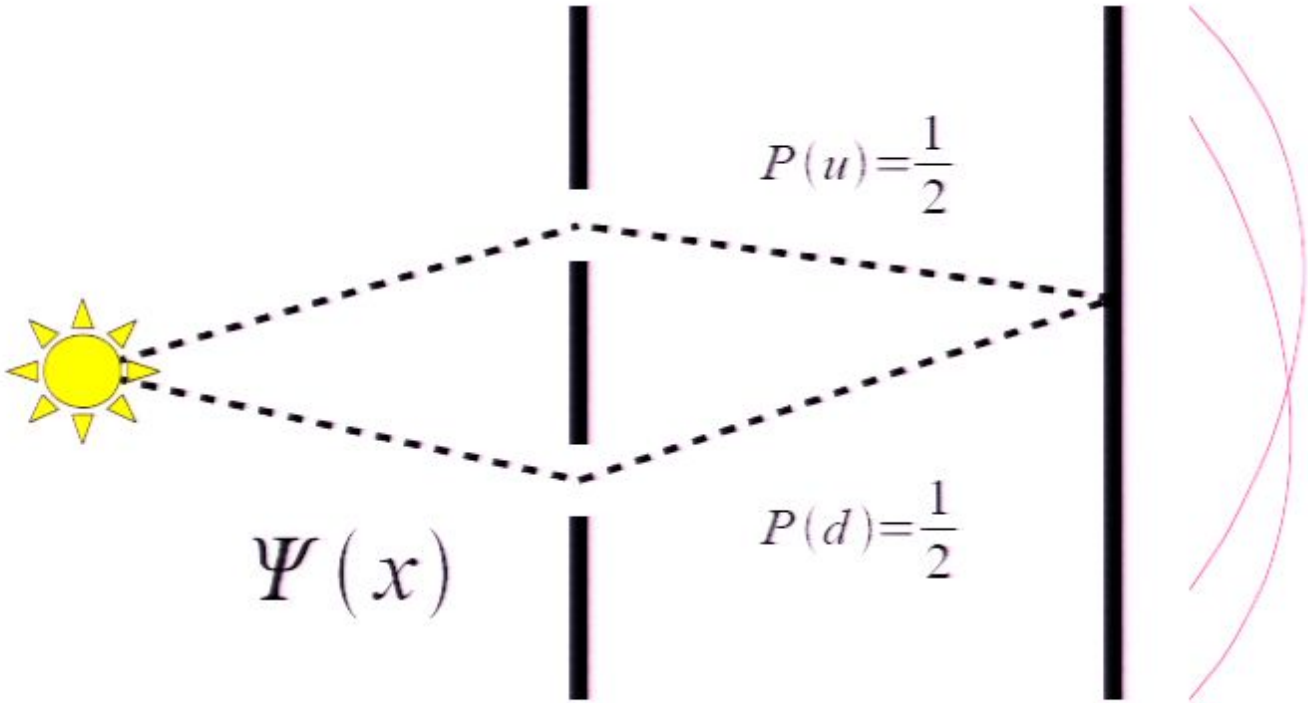
$$P(x|u)=|\psi_u(x)|^2$$

$$\psi_u(x)=|\psi_u(x)|e^{iS_u(x}$$

$$\psi_d(x)=|\psi_d(x)|e^{iS_d(x}$$

$$P(x|d)=|\psi_d(x)|^2$$

Quantum phenomena : interferometry



$$P(x|u)=|\psi_u(x)|^2$$

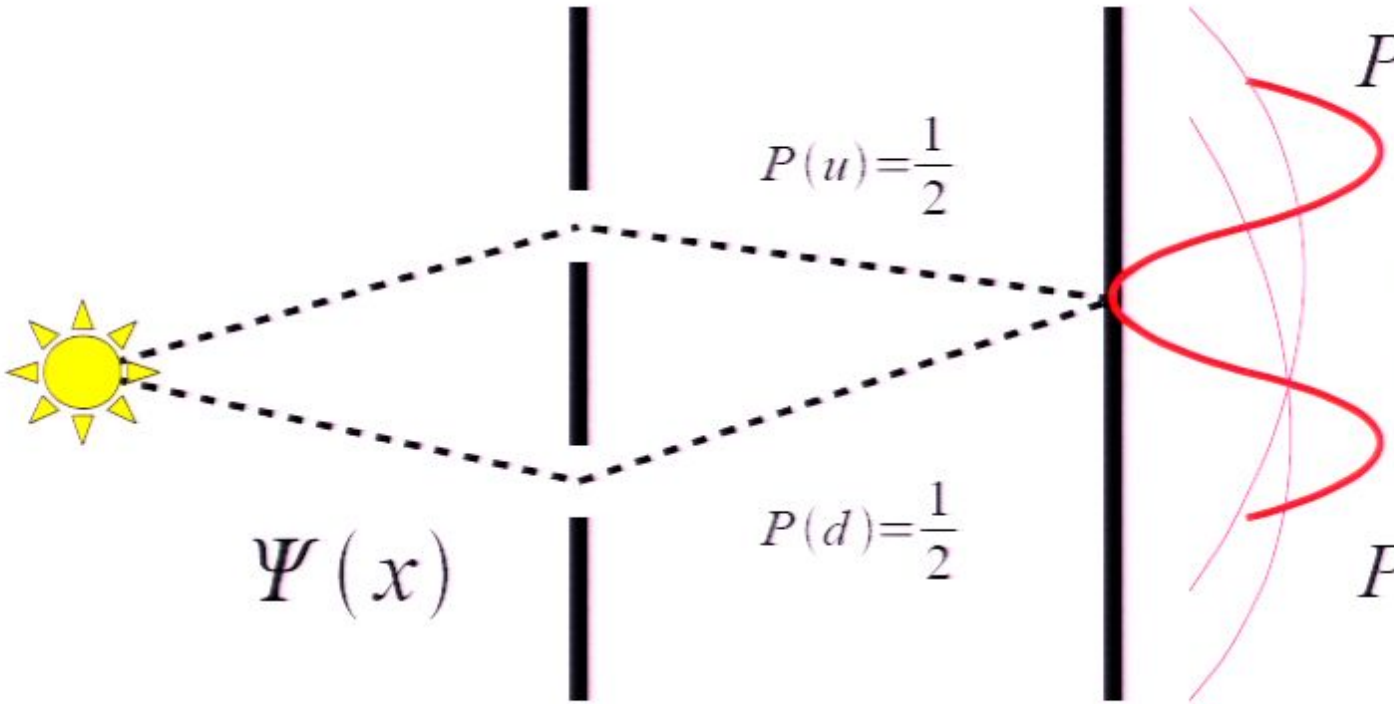
$$\psi_u(x)=|\psi_u(x)|e^{iS_u(x}$$

$$\psi_d(x)=|\psi_d(x)|e^{iS_d(x}$$

$$P(x|d)=|\psi_d(x)|^2$$

$$P(x|u)P(u)+P(x|d)P(d)=\frac{1}{2}\left(|\psi_u(x)|^2+|\psi_d(x)|^2\right)$$

Quantum phenomena : interferometry

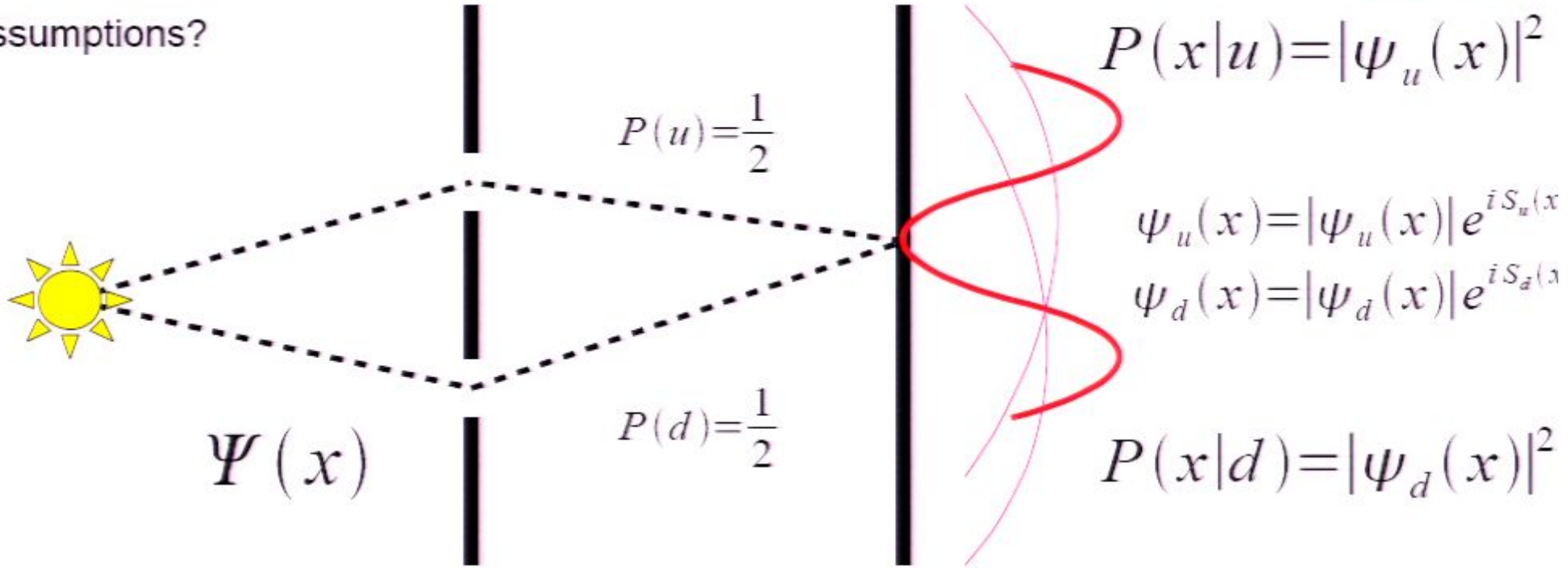


$$P(x|u)P(u)+P(x|d)P(d)=\frac{1}{2}\left(|\psi_u(x)|^2+|\psi_d(x)|^2\right)$$

$$P(x)=\Psi^*(x)\Psi(x)=\frac{1}{2}\left(|\psi_u(x)|^2+|\psi_d(x)|^2+2|\psi_u(x)||\psi_d(x)|\cos(S_u(x)-S_d(x))\right)$$

Quantum phenomena : interferometry

Assumptions?



$$P(x|u)=|\psi_u(x)|^2$$

$$P(u)=\frac{1}{2}$$

$$\psi_u(x)=|\psi_u(x)|e^{iS_u(x}$$

$$\psi_d(x)=|\psi_d(x)|e^{iS_d(x}$$

$$\Psi(x)$$

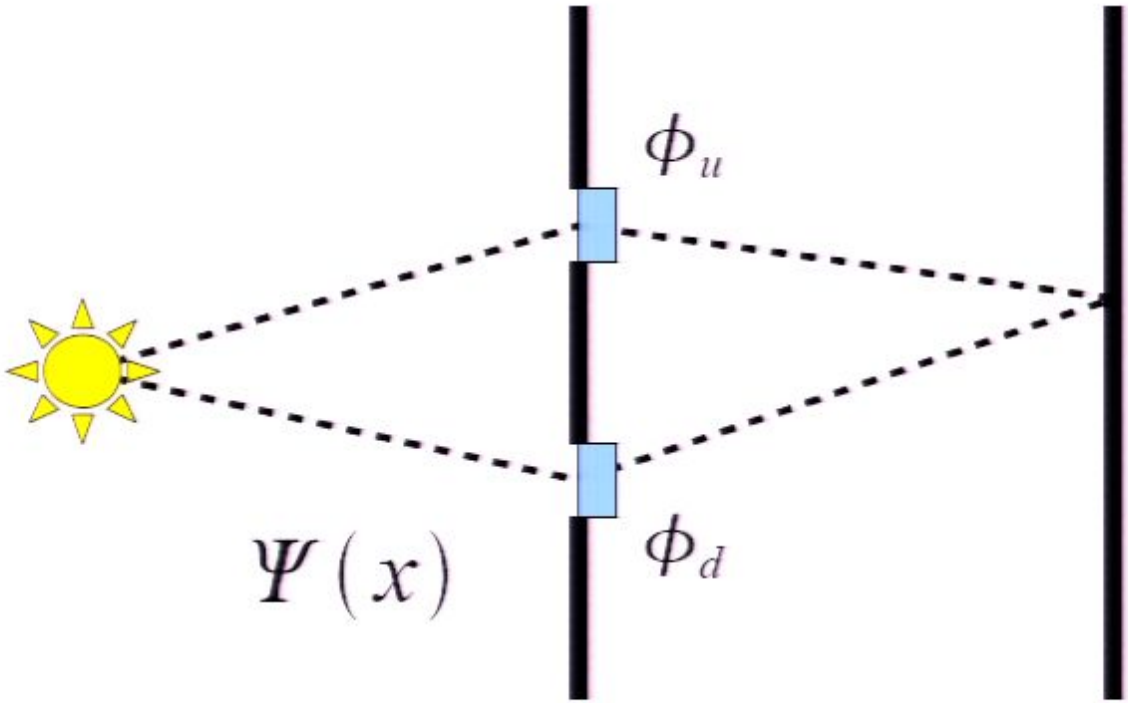
$$P(d)=\frac{1}{2}$$

$$P(x|d)=|\psi_d(x)|^2$$

$$P(x|u)P(u)+P(x|d)P(d)=\frac{1}{2}\left(|\psi_u(x)|^2+|\psi_d(x)|^2\right)$$

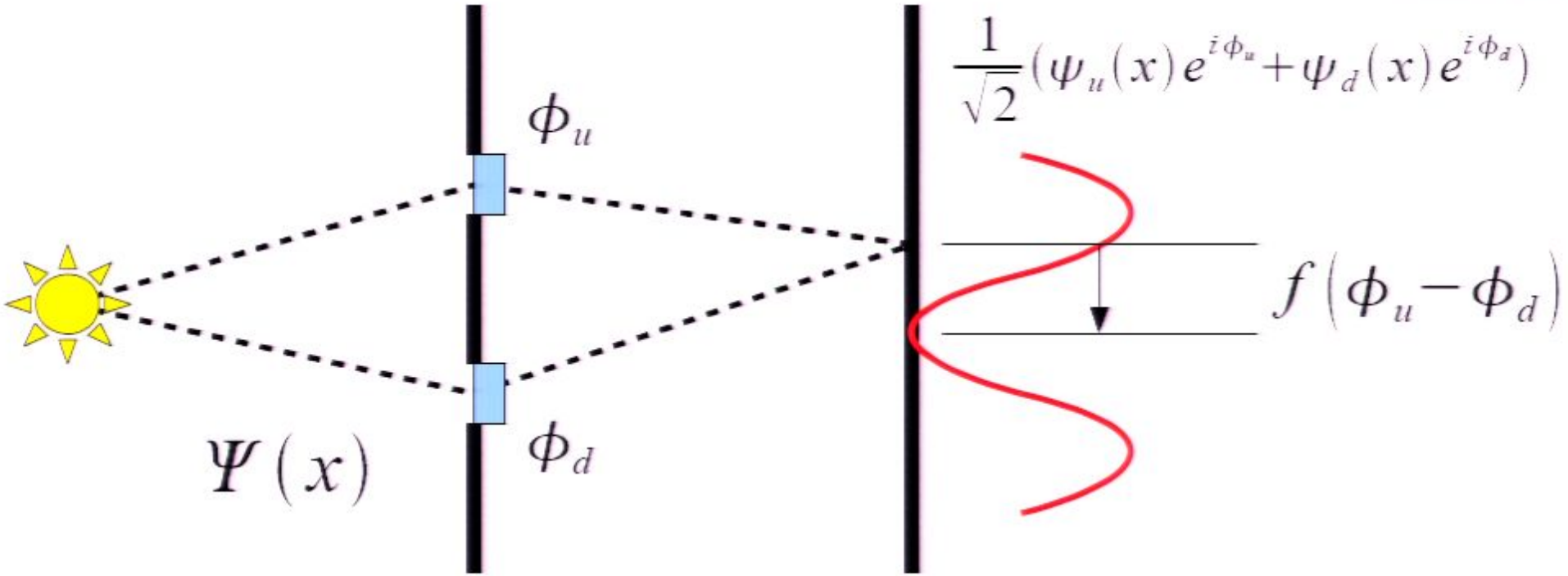
$$P(x)=\Psi^*(x)\Psi(x)=\frac{1}{2}\left(|\psi_u(x)|^2+|\psi_d(x)|^2+2|\psi_u(x)||\psi_d(x)|\cos(S_u(x)-S_d(x))\right)$$

Quantum phenomena : interferometry



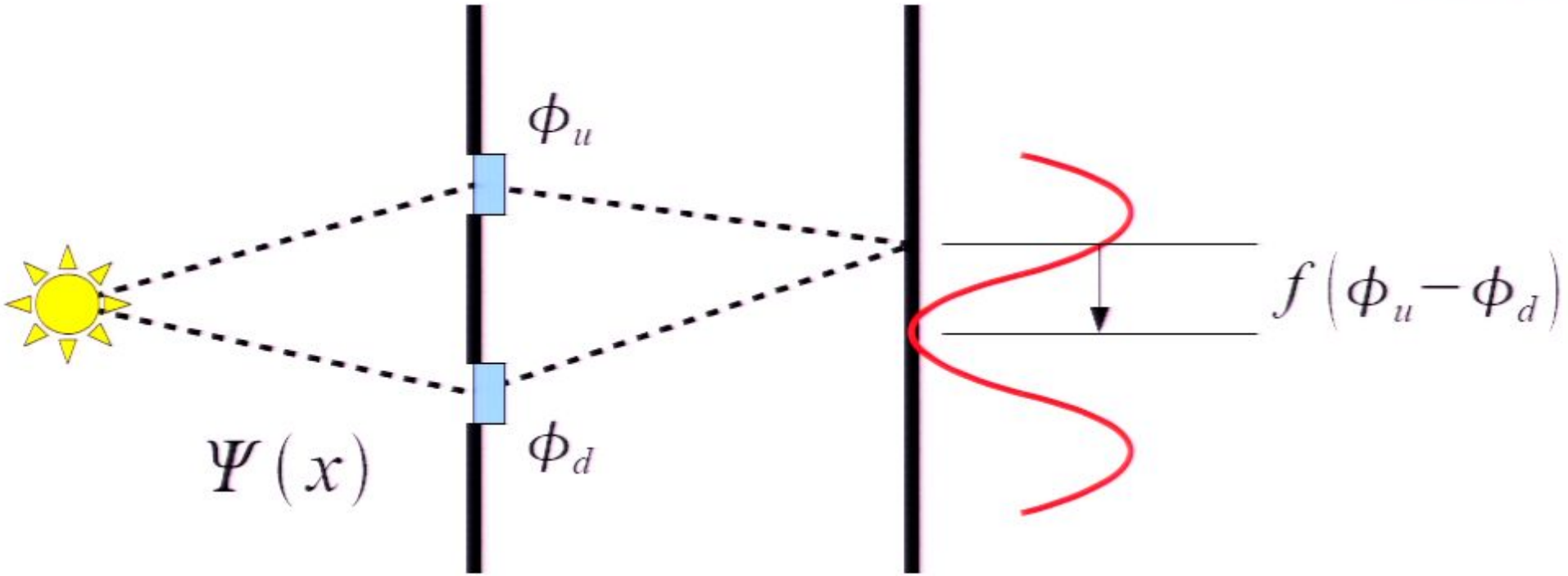
$$\frac{1}{\sqrt{2}}(\psi_u(x)e^{i\phi_u}+\psi_d(x)e^{i\phi_d})$$

Quantum phenomena : interferometry



$$P(x)=\frac{1}{2}\left(|\psi_u(x)|^2+|\psi_d(x)|^2+2|\psi_u(x)||\psi_d(x)|\cos(S_u(x)+\phi_u-S_d(x)-\phi_d)\right)$$

Quantum phenomena : interferometry



"In any attempt of a pictorial representation of the behaviour of the photon we would, thus, meet with the difficulty: to be obliged to say, on the one hand, that the photon always chooses *one* of the two ways and, on the other hand, that it behaves as if it had passed *both* ways." Bohr

Quantum phenomena : interferometry

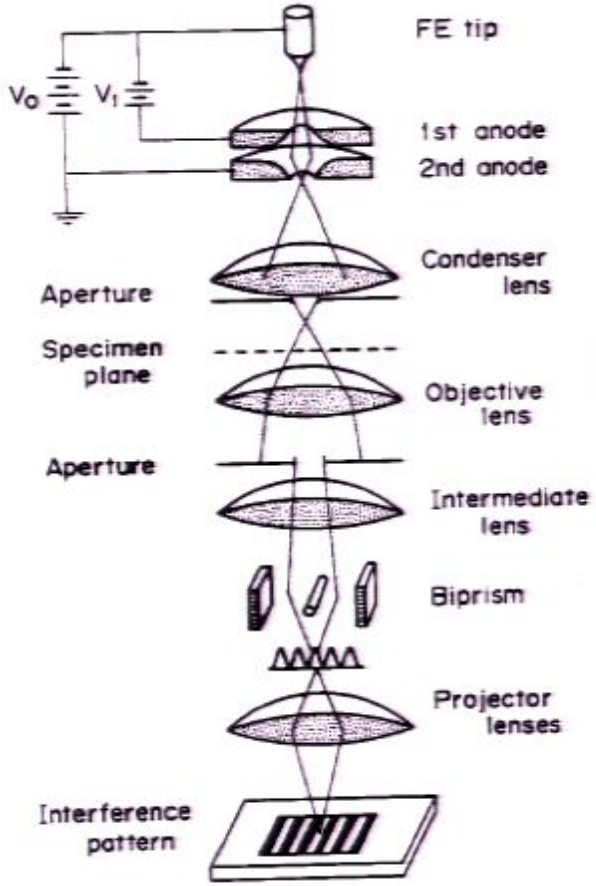


Figure 1.1. Electron interference with a field-emission electron microscope. Wave front splitting occurs at the biprism. (Courtesy of A. Tonomura, Hitachi ARL.)

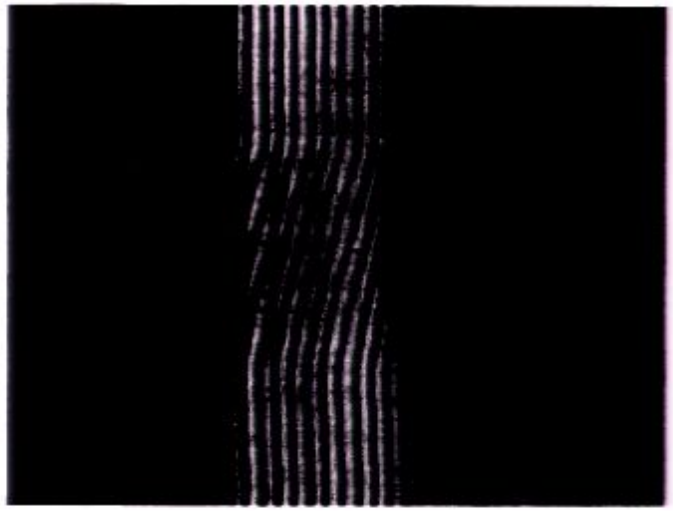


Figure 1.6. Demonstration of electron-wave phase shift in the presence of a vector potential field (AB effect) in the Bayh experiment. The magnetic field is held constant in the upper and lower third of the figure; in the middle third the variation in interference fringes follows a linear variation in magnetic field strength. (Adapted from Bayh [19].)

Source:
More than one mystery
Silverman, pg.2, 16

Quantum phenomena : interferometry

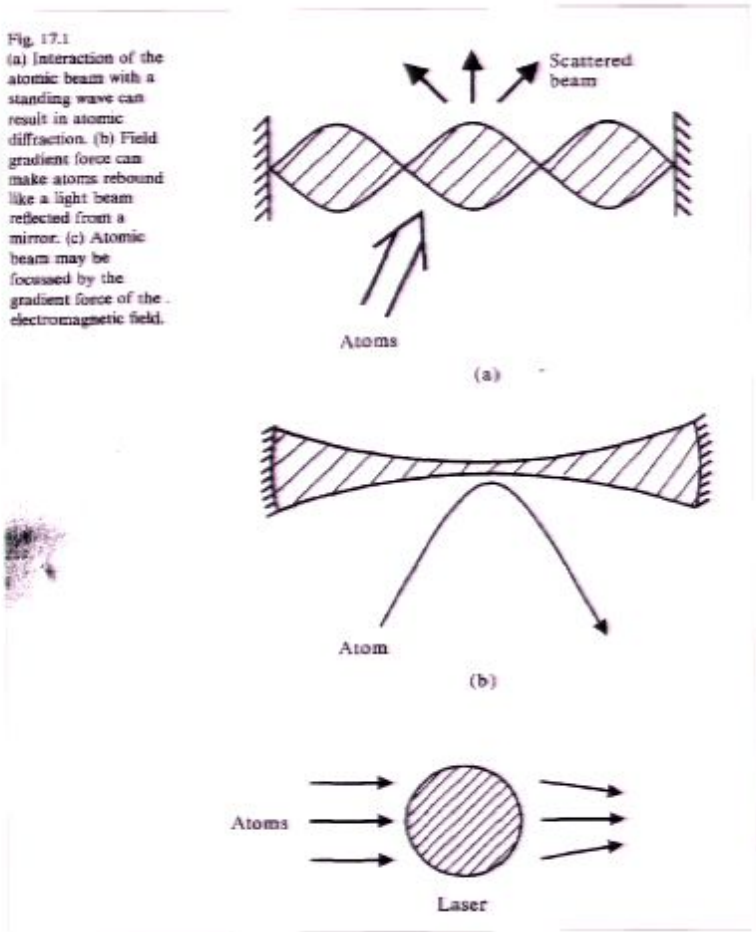


Fig. 17.1
(a) Interaction of the atomic beam with a standing wave can result in atomic diffraction. (b) Field gradient force can make atoms rebound like a light beam reflected from a mirror. (c) Atomic beam may be focussed by the gradient force of the electromagnetic field.

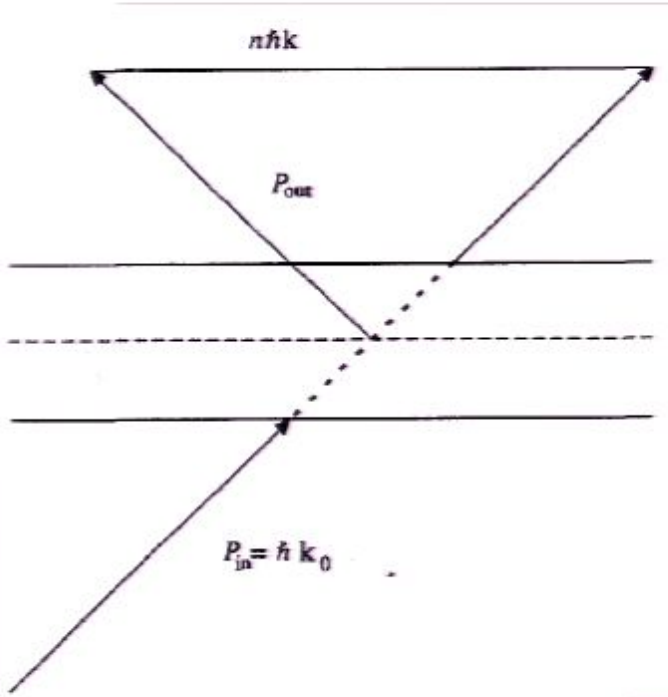
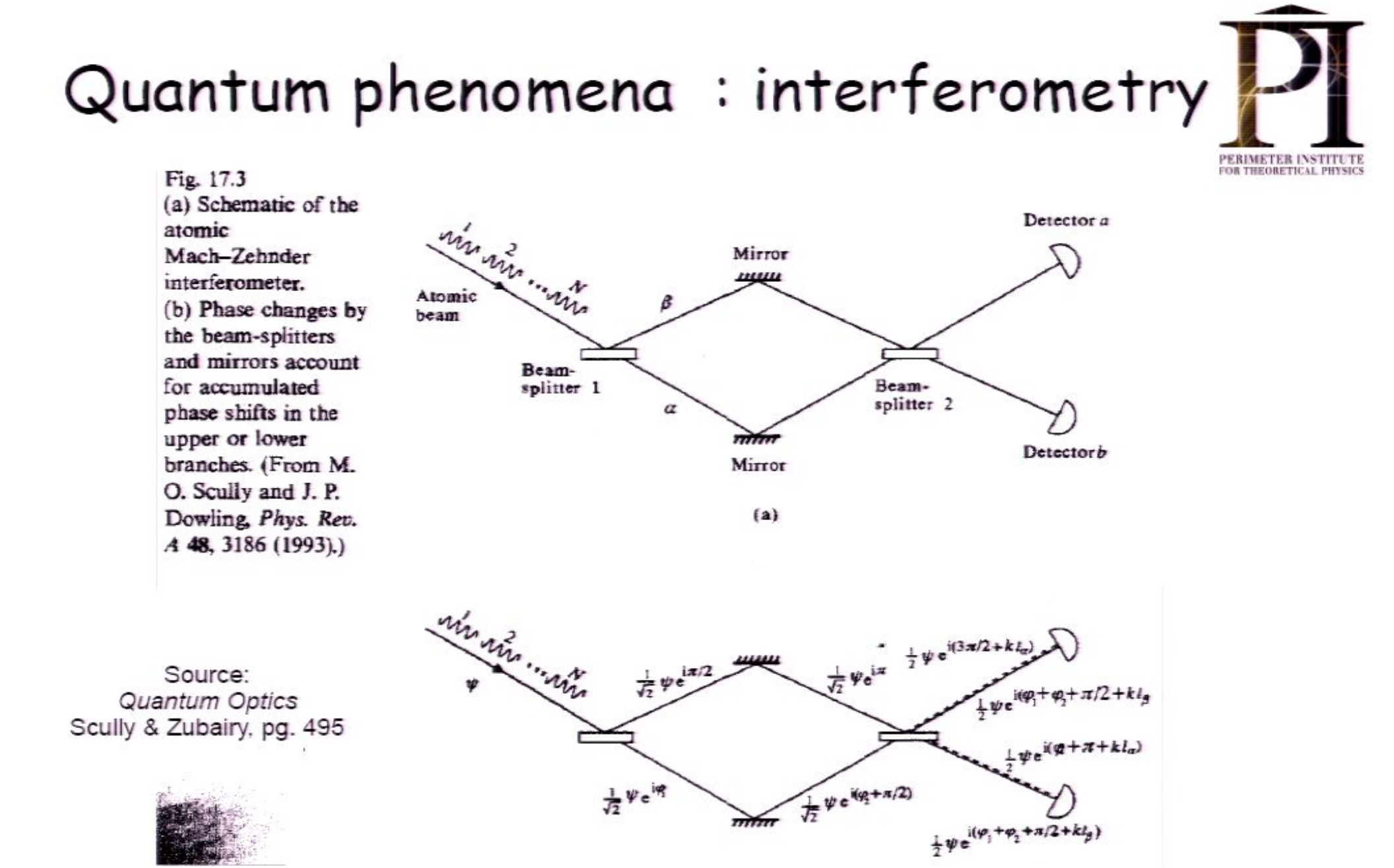


Fig. 17.2
An atomic beam of wave vector $\mathbf{k}_0$ can acquire a momentum $n\hbar\mathbf{k}$ during passage through a standing wave resulting in atomic diffraction.

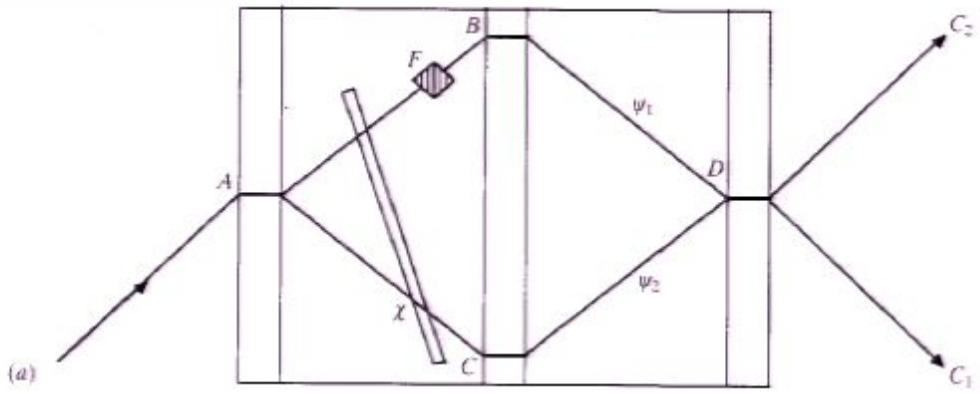
Source:
Quantum Optics
Scully & Zubairy, pg. 491,492

Quantum phenomena : interferometry



Source:
Quantum Optics
Scully & Zubairy, pg. 495

Quantum phenomena : interferometry



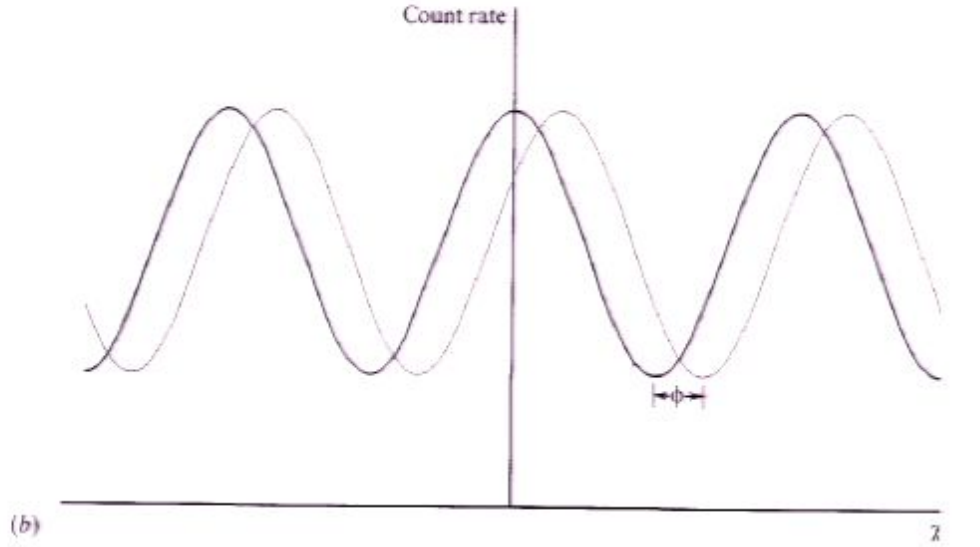
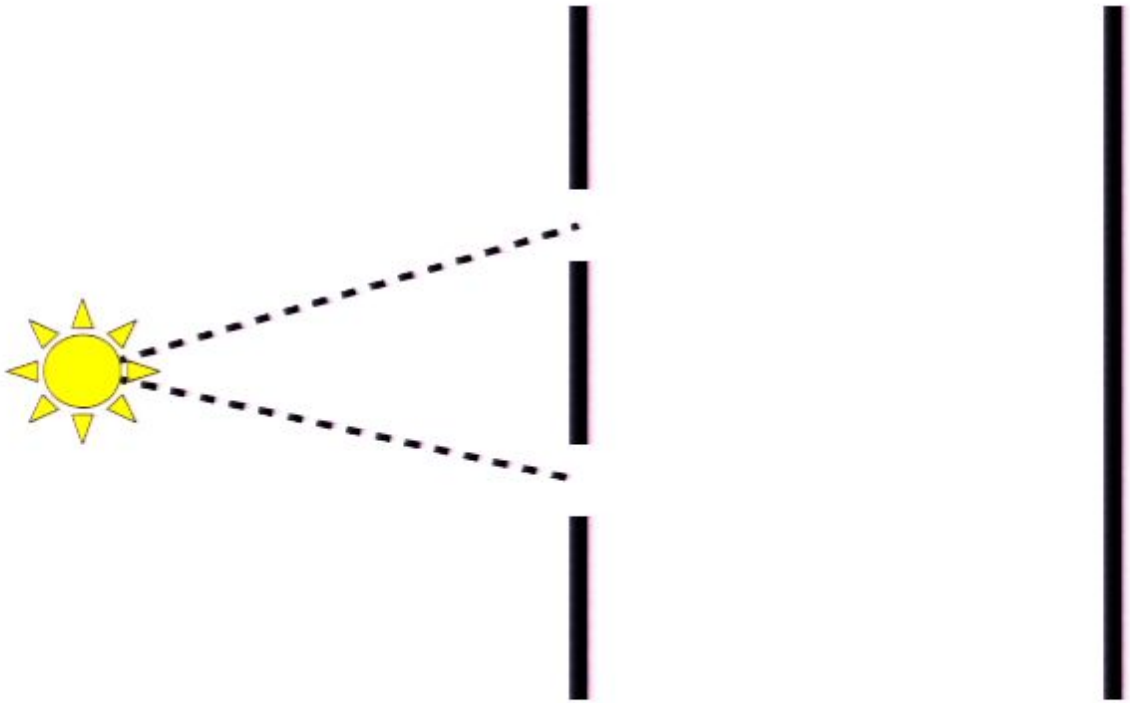


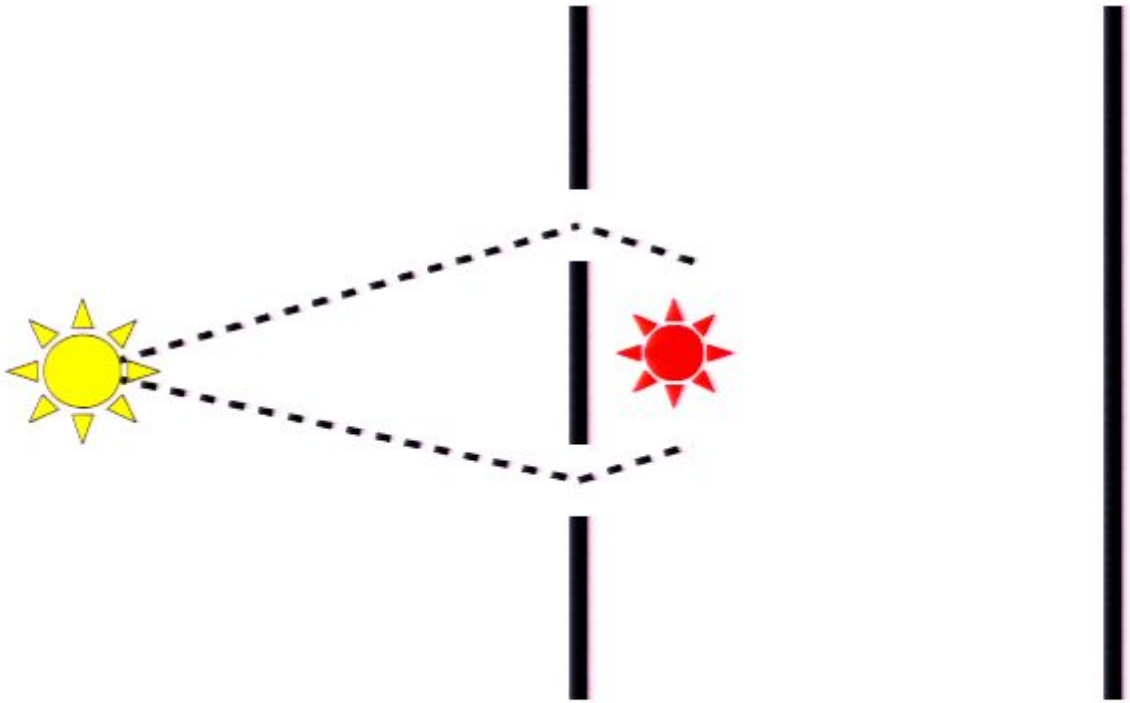
Fig. 5.13 (*a*) The perfect crystal neutron interferometer described in the text. (*b*) The interference pattern displayed in the count rate of C_1 and C_2 obtained by varying the relative phase χ between the split beams. An additional phase shift ϕ due to some external agent is manifested by changes in the count rate for each setting of χ.

Source:
The Quantum Theory of Motion
Holland, pg. 205

Quantum phenomena : interferometry

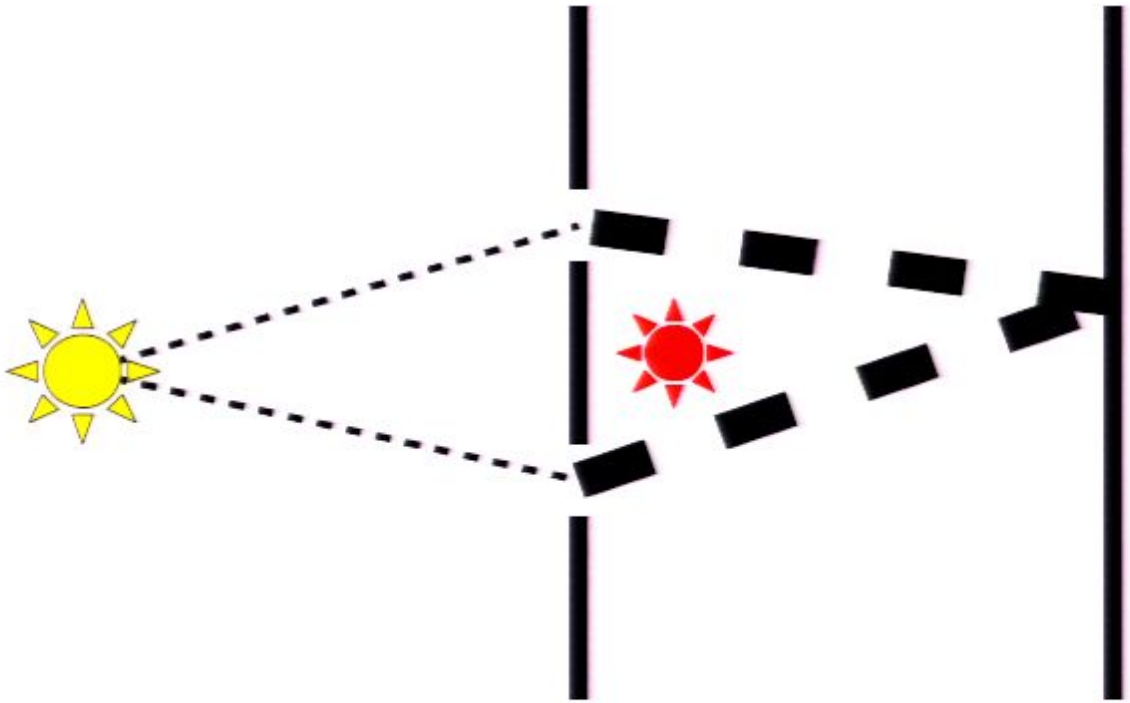


Quantum phenomena : interferometry



Shine a light to see where it went

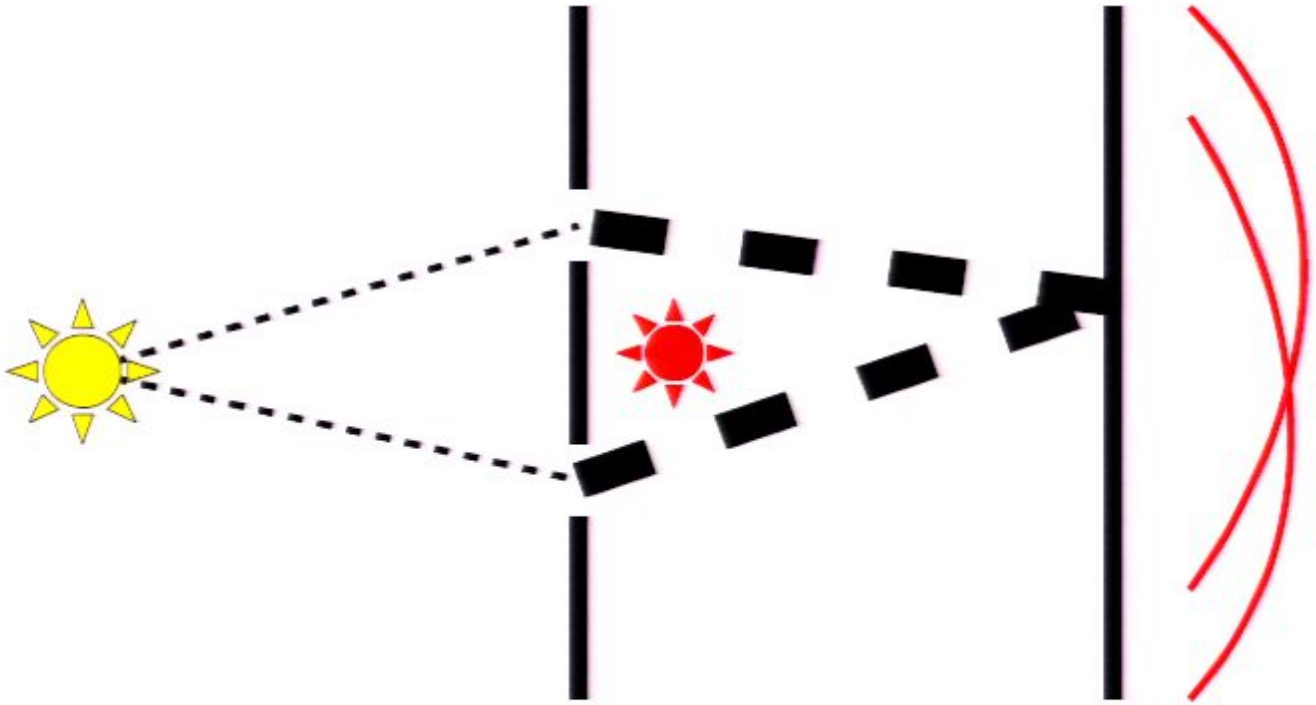
Quantum phenomena : interferometry



$$\delta p \approx 2\pi \frac{\hbar}{\lambda}$$

Interaction affects momentum of particle

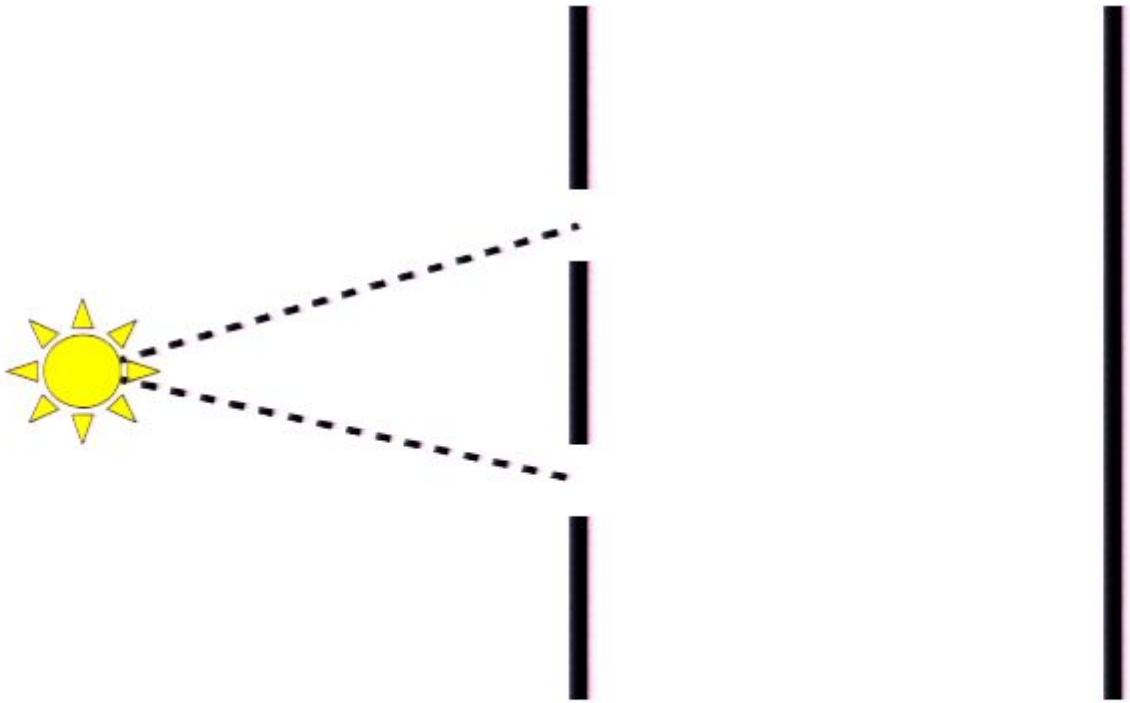
Quantum phenomena : interferometry



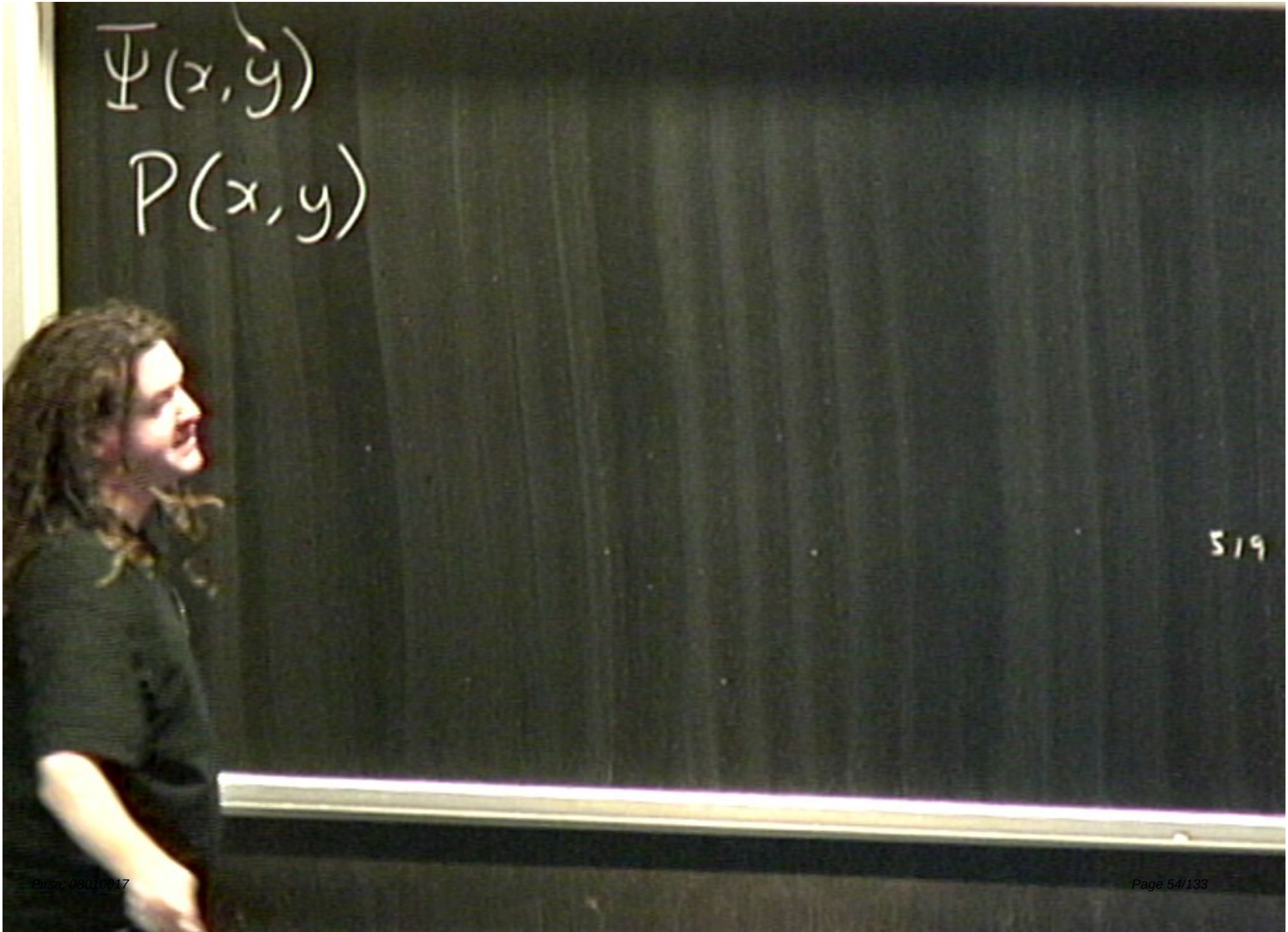
$$\delta p \approx 2\pi \frac{\hbar}{\lambda}$$

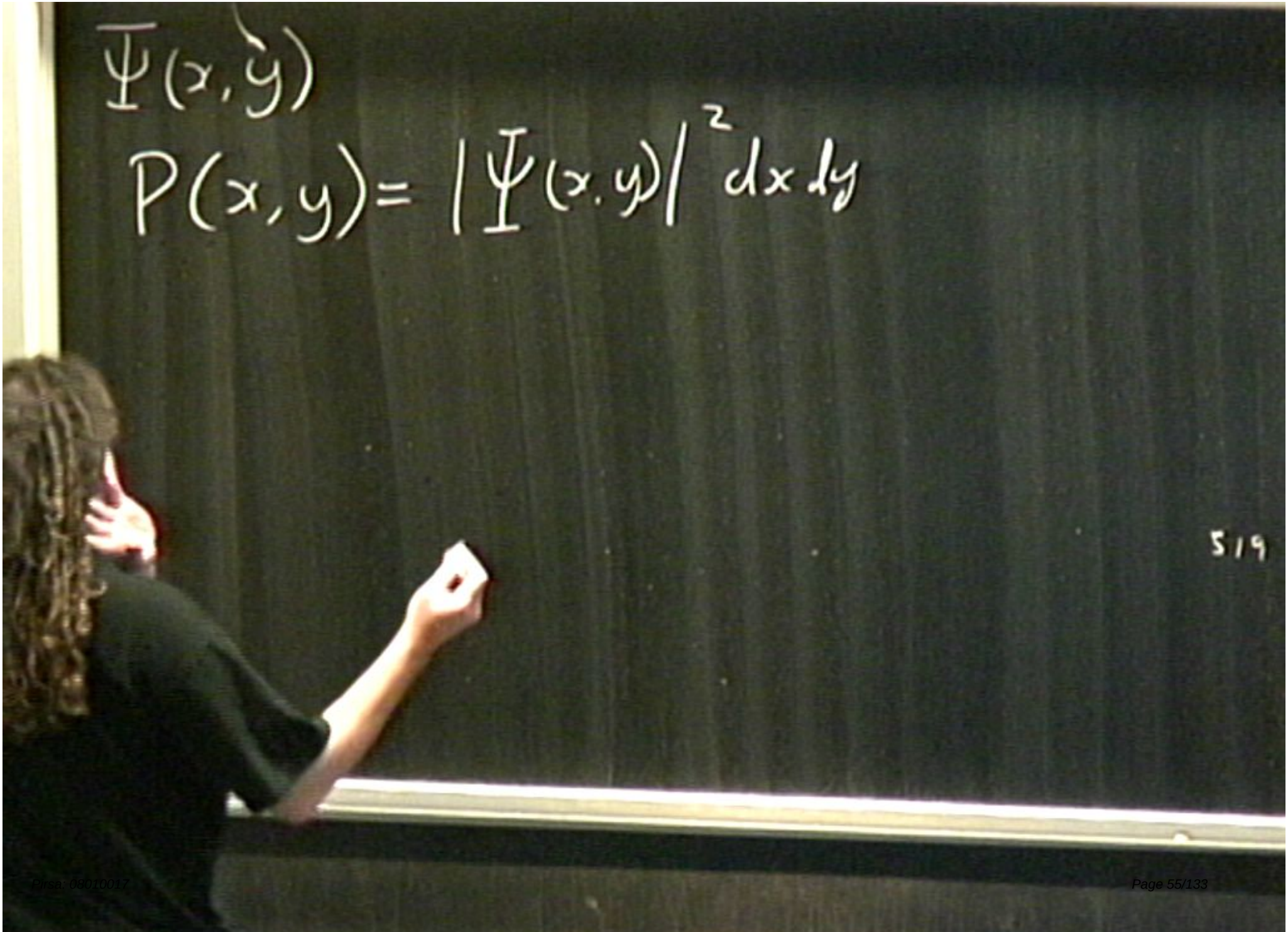
Complementarity of position and momentum?

Quantum phenomena : interferometry




$\overline{\Psi}(x,\bar{y})$
5/9


$\overline{\Psi}(x,y)$
$P(x,y)$
5/9

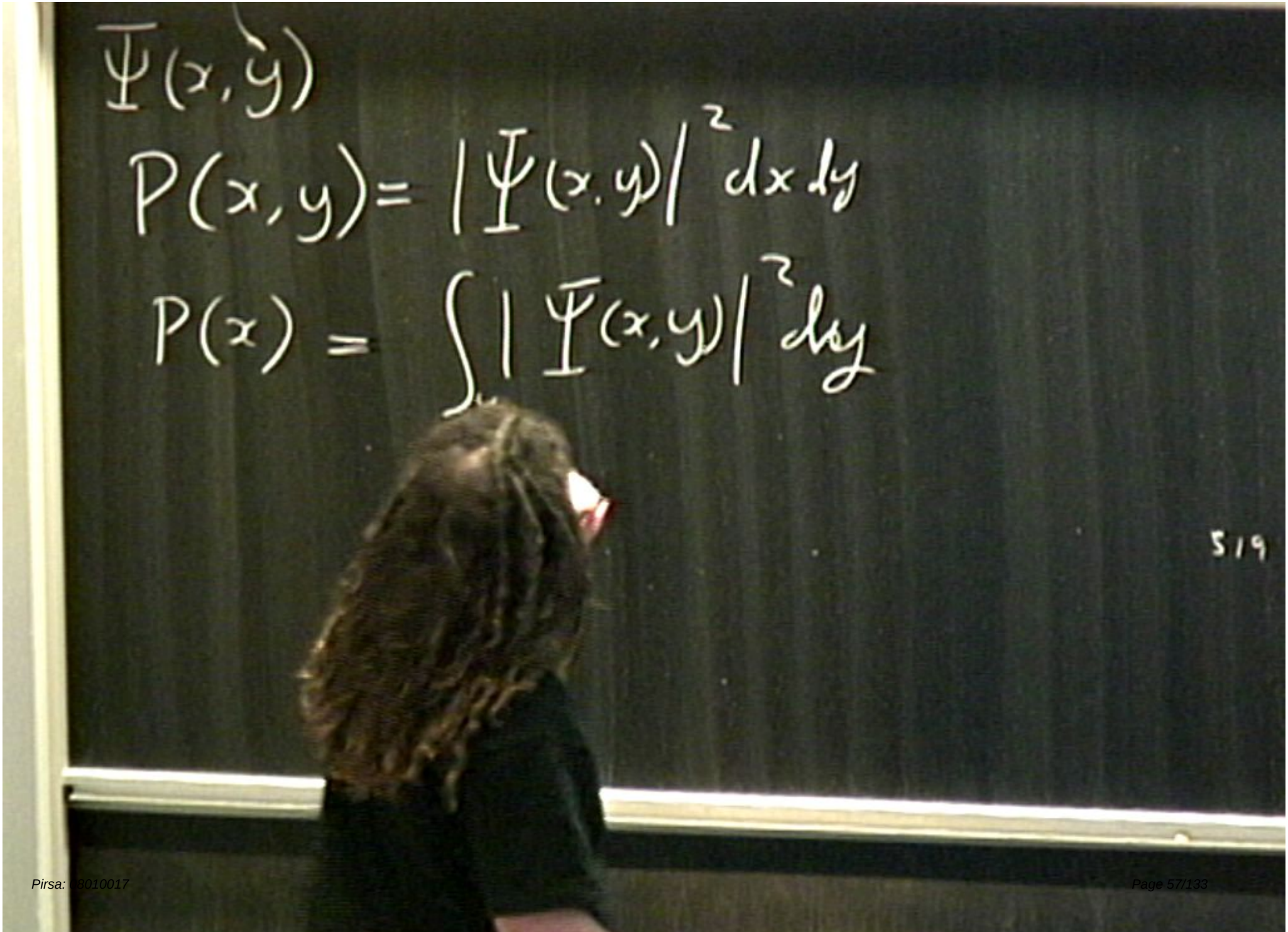

$\Psi(x,y)$
$P(x,y) = |\Psi(x,y)|^2 dx\,dy$
5/9

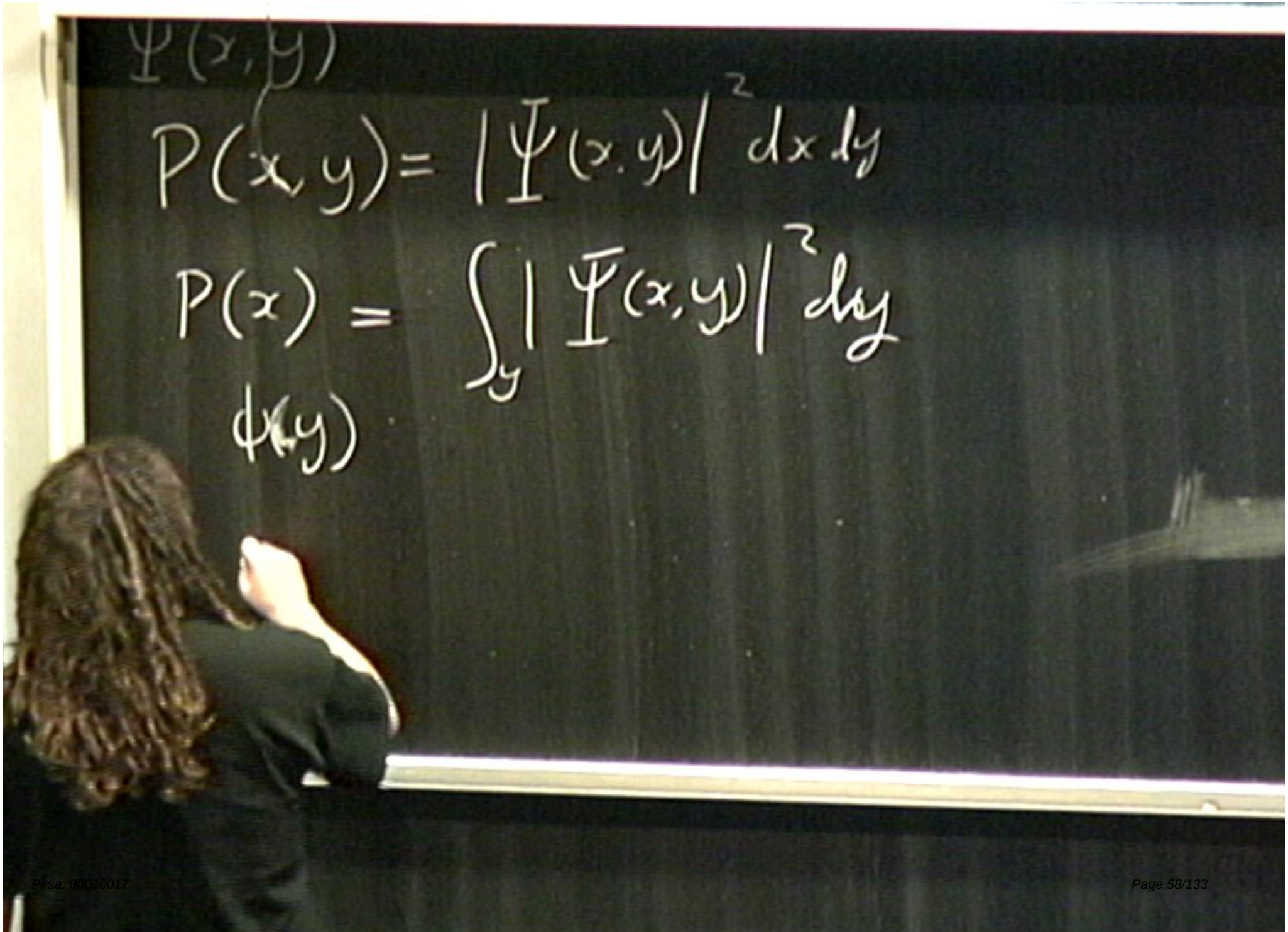
$\Psi(x,y)$

$P(x,y) = |\Psi(x,y)|^2 dx\,dy$

$P(x)$

5/9


$\Psi(x,y)$
$P(x,y) = |\Psi(x,y)|^2 dx\,dy$
$P(x) = \int |\Psi(x,y)|^2 dy$
5/9


Ψ(x,y)
P(x,y) = |Ψ(x,y)|² dx dy
P(x) = ∫_y |Ψ(x,y)|² dy
φ(y)

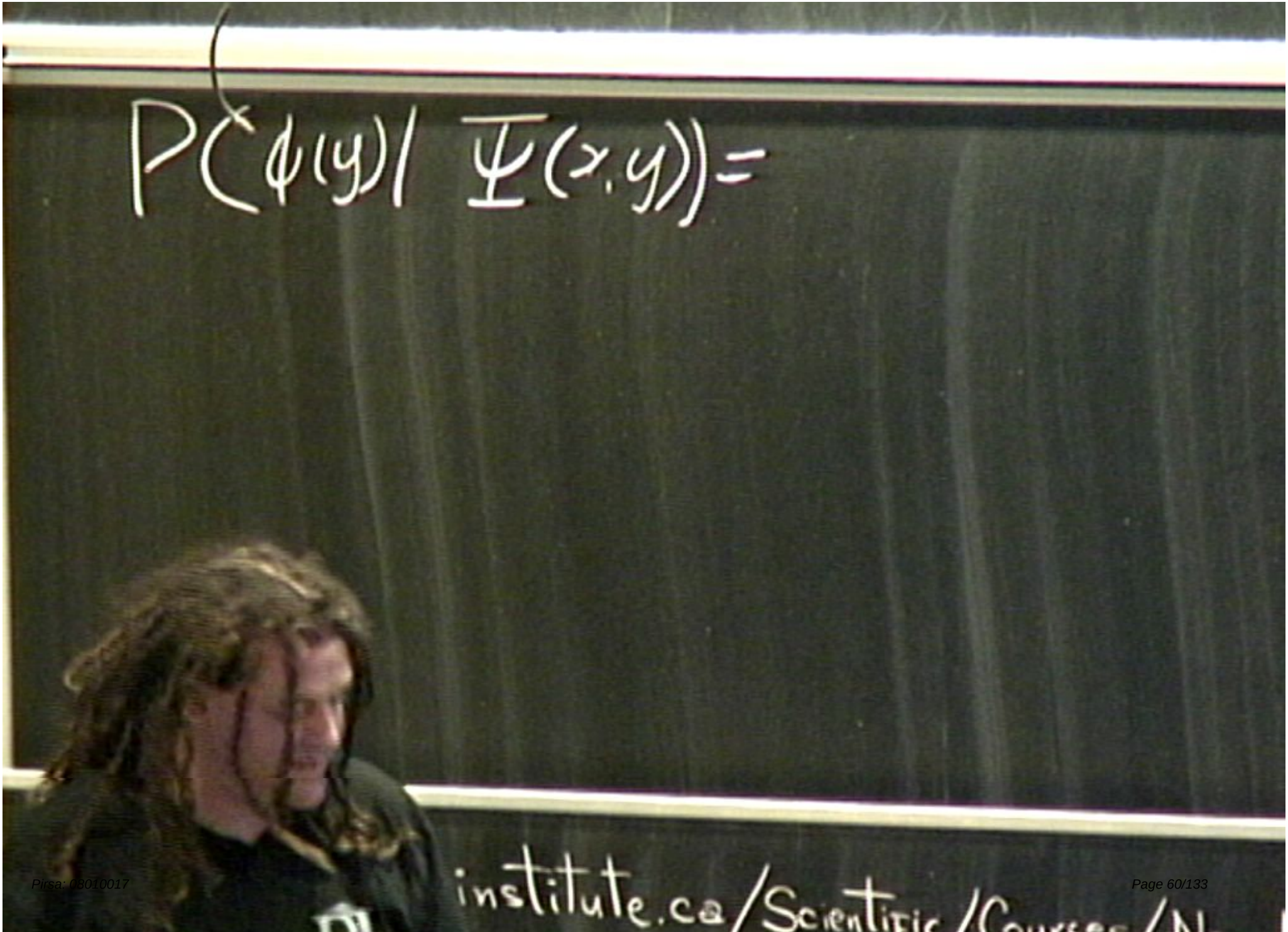
$\Psi(x,y)$

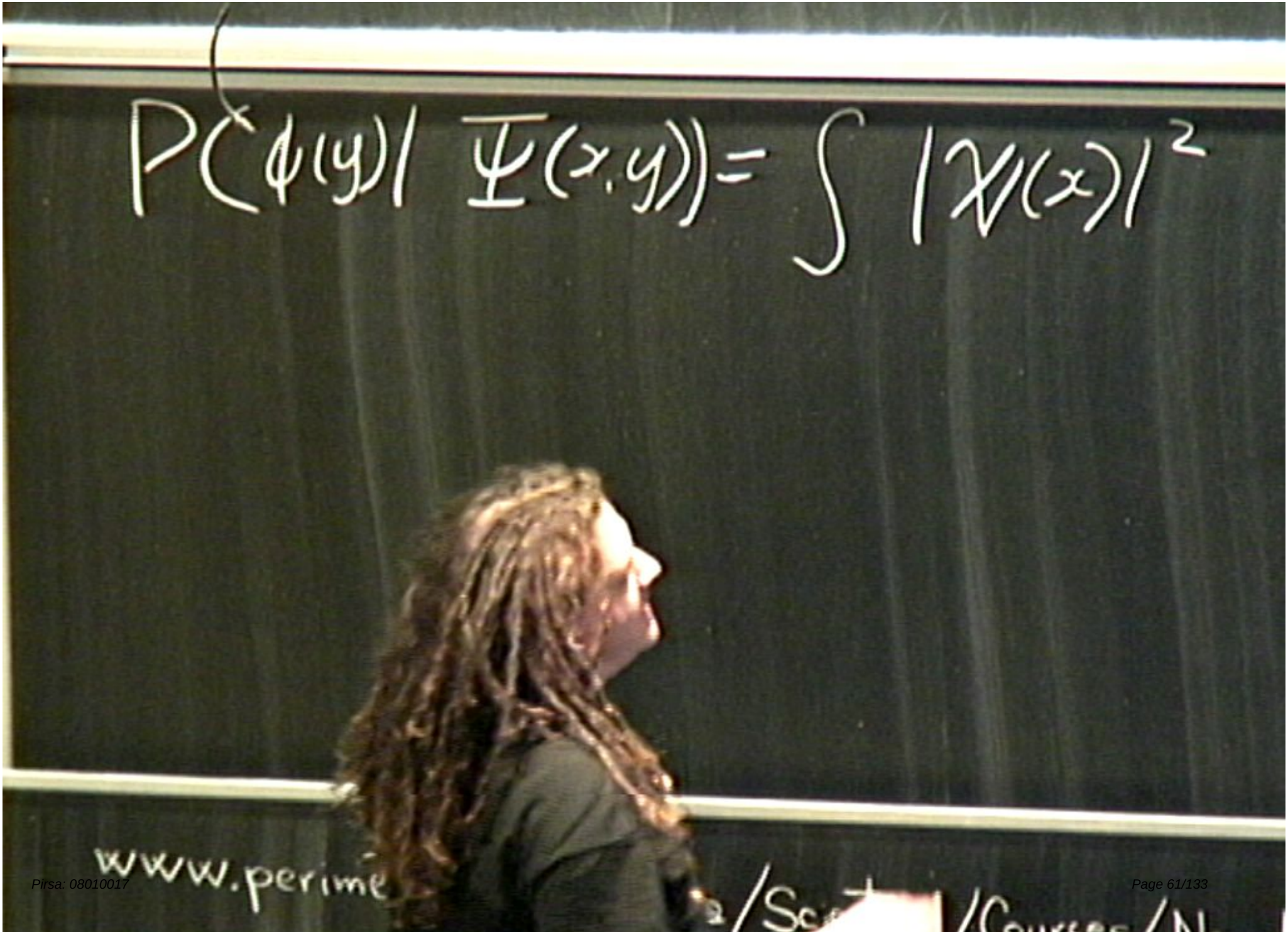
$P(x,y) = |\Psi(x,y)|^2 \, dx\,dy$

$P(x) = \int_y |\Psi(x,y)|^2 \, dy$

$\phi(y)$

$\chi(x) = \int \phi^*(y)\, \Psi(x,y)\, dy$


P(φ(y)| Ψ(x,y))=
institute.ca/Scientific/Courses/N


$P(\phi(y)|\Psi(x,y)) = \int |\chi(x)|^2$
www.perime

$$P(\phi(y) | \Psi(x,y)) = \int_x |\chi(x)|^2 dx$$

www.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundamental_Physics

$\Psi(x)$ $\phi(x)$

$$P(\phi(y) | \Psi(x,y)) = \int_x |\chi(x)|^2 dx$$

rinstitute.ca/Scientific/Courses/New_Horizons_in_Fundam
Physi

$$\phi(x)$$

$$P(\phi(y) \mid \Psi(x,y)) = \int_x |\chi(x)|^2 dx$$

$\Psi'(x,y)$

www.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundamental_Physics

$\psi(x)$ $\phi(x)$

$$P(\phi(y) \mid \Psi(x,y)) = \int_x |\chi(x)|^2 dx$$

$$\Psi'(x,y) = \phi(y)$$

www.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundam
Physi

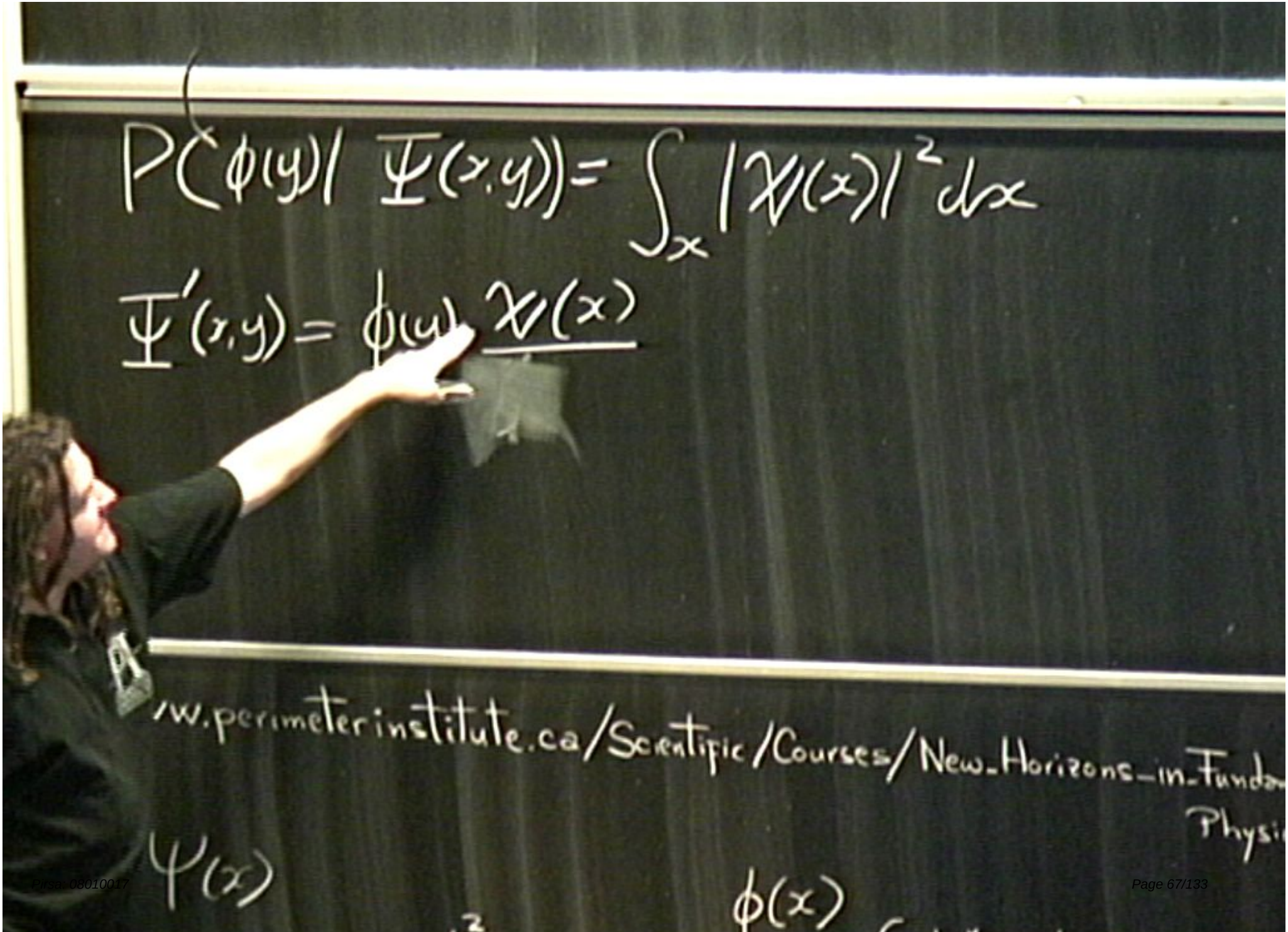
$\Psi(x)$ $\phi(x)$

$$P(\phi(y) | \Psi(x,y)) = \int_x |\chi(x)|^2 dx$$

$$\Psi'(x,y) = \phi(y) \frac{\chi(x)}{\sqrt{\Delta}}$$

www.perimeterinstitute.ca/Scientific/Courses/Ne

$\Psi(x)$ $\phi(x)$


$P(\phi(y) | \Psi(x,y)) = \int_x |\chi(x)|^2 dx$
$\Psi'(x,y) = \phi(y)\,\chi(x)$
/w.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundam
Physi
$\psi(x)$
$\phi(x)$

$$P(\phi(y) | \Psi(x,y)) = \int_x |\chi(x)|^2 dx$$

$$\Psi'(x,y) = \phi(y) \frac{\chi(x)}{\sqrt{P(\phi(y) | \Psi(x,y))}}$$

ww.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundam
Physi

$\phi(x)$

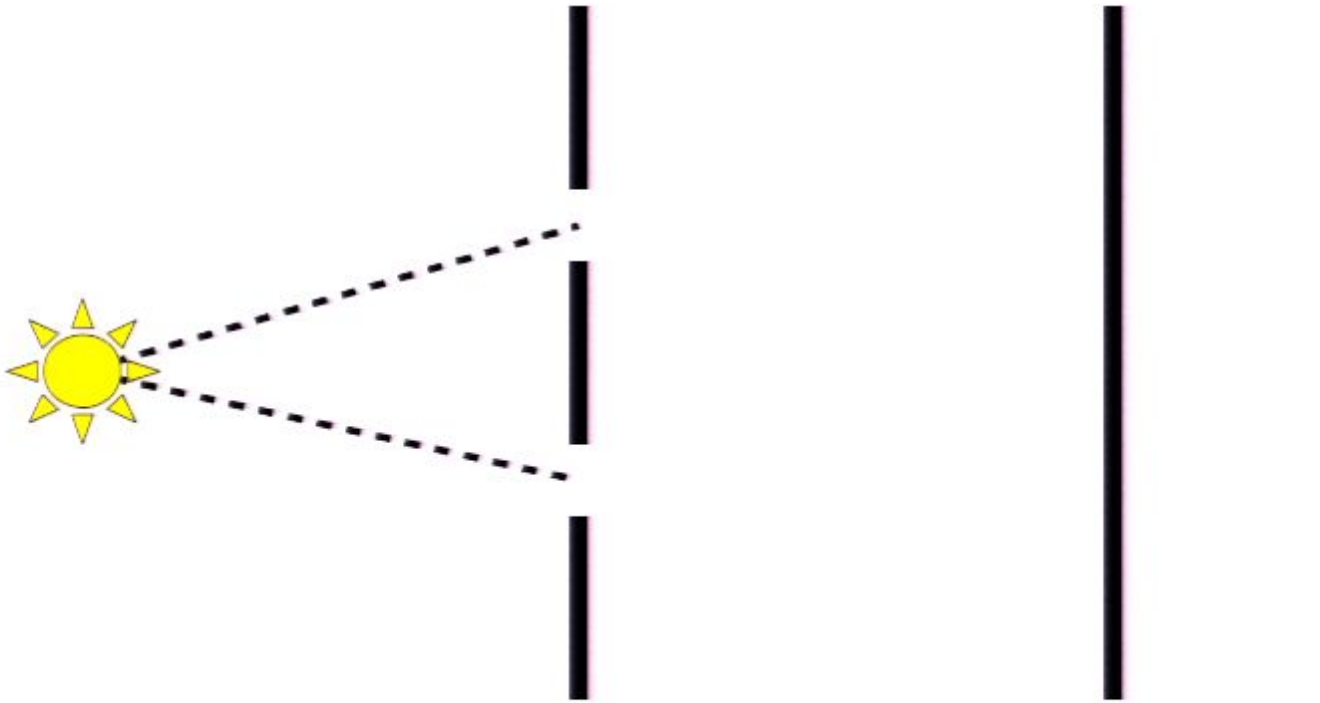
$$P(\phi(y) | \Psi(x,y)) = \int_x |\chi(x)|^2 dx$$

$$\Psi'(x,y) = \phi(y) \frac{\chi(x)}{\sqrt{P(\phi(y) | \Psi(x,y))}}$$

www.perimeterinstitute.ca/Scientific/Courses/New_Horizons_in_Fundam
Physi

$\psi(x)$ $\phi(x)$

Quantum phenomena : interferometry

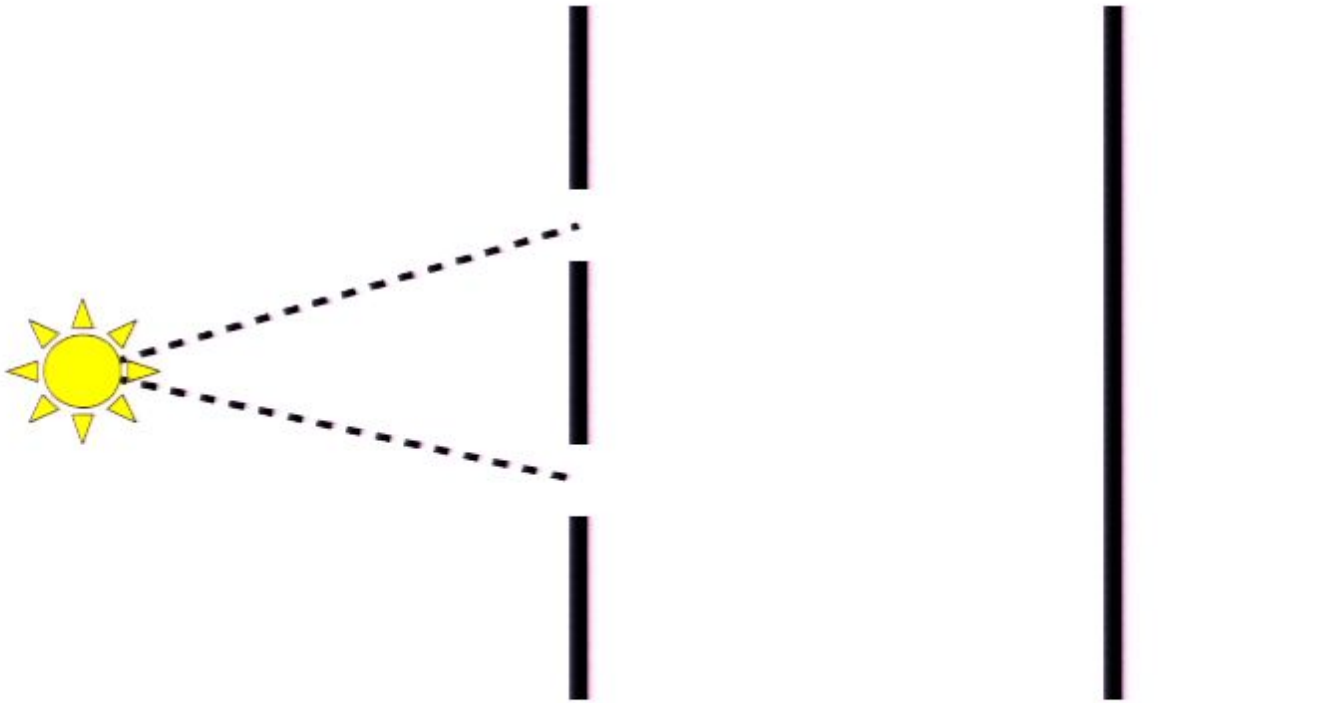


$\psi(e)\xi(0)$ $\psi(g)\xi(1)$

Negligible momentum change

Optical QED Cavity

Quantum phenomena : interferometry

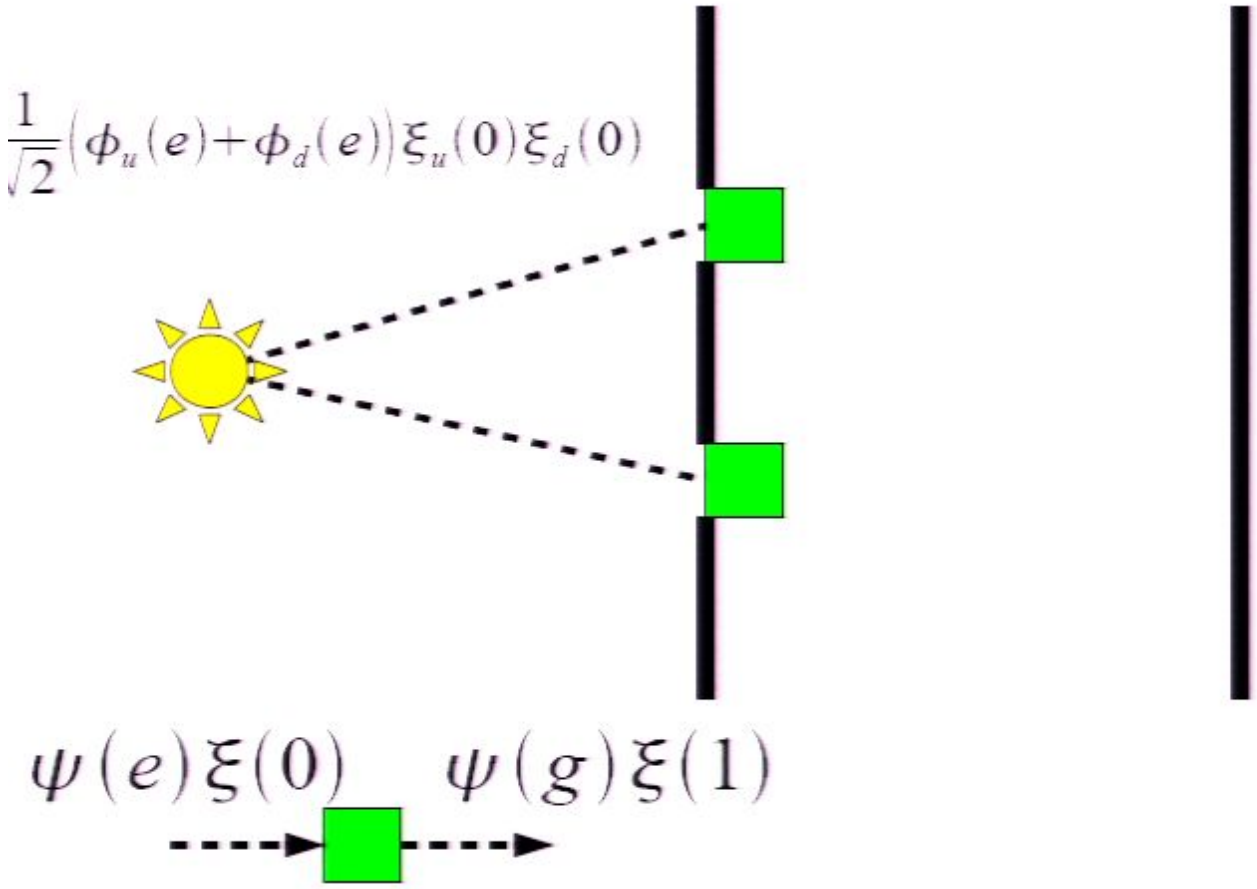


$\psi(e)\xi(0)$ $\psi(g)\xi(1)$

Negligible momentum change

Optical QED Cavity

Quantum phenomena : interferometry



Optical QED Cavity

$$\frac{1}{\sqrt{2}}\left(\phi_u(e) - \phi_d(e)\right)\xi_u(0)\xi_d(0)$$

$$\frac{1}{\sqrt{2}}\left(\phi_u(e) - \phi_d(e)\right)\xi_u(0)\xi_d(0)$$

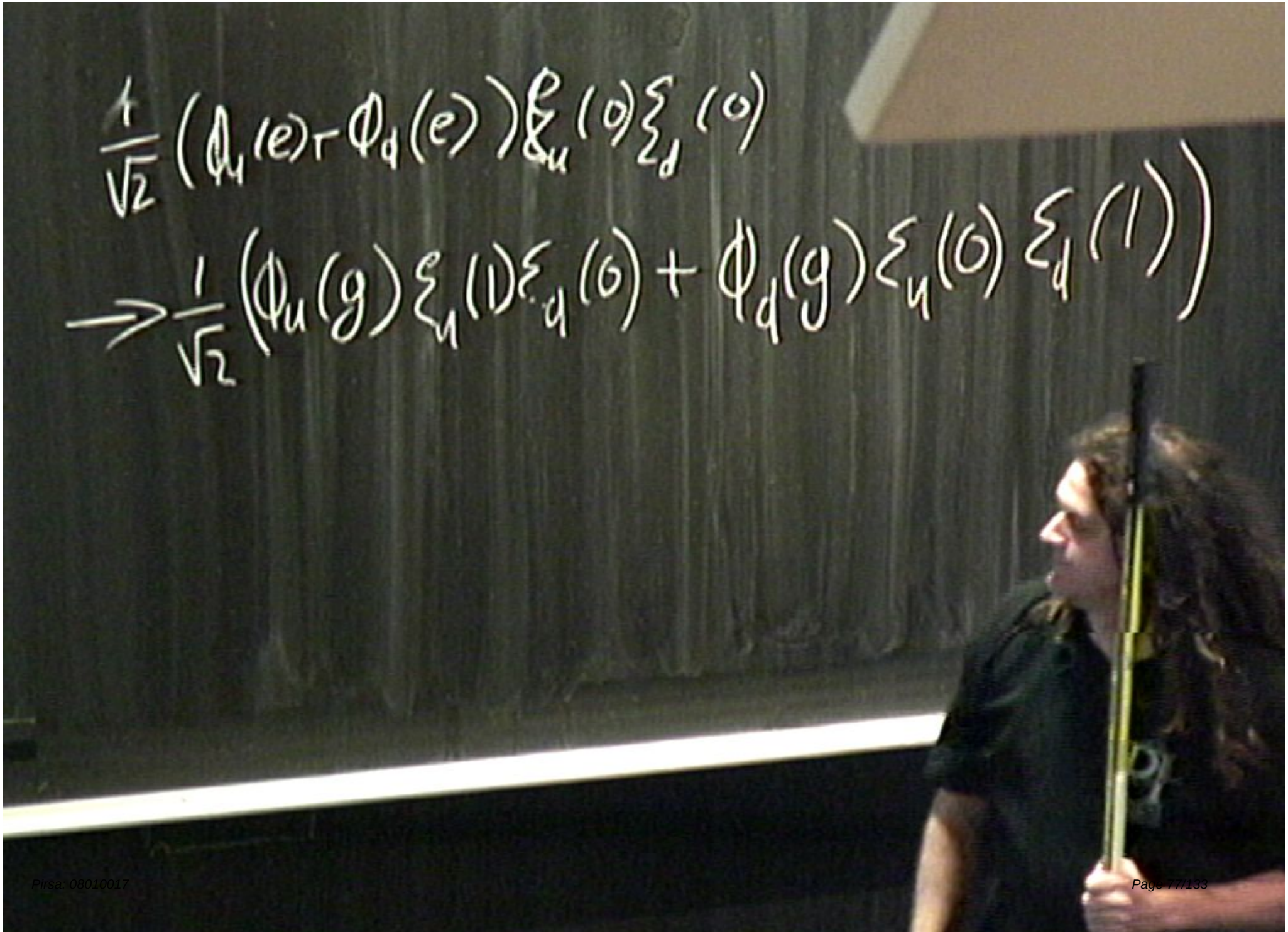
$$\Rightarrow \frac{1}{\sqrt{2}}$$

$$\frac{1}{\sqrt{2}}\left(\phi_u(e) - \phi_d(e)\right)\xi_u(0)\xi_d(0)$$

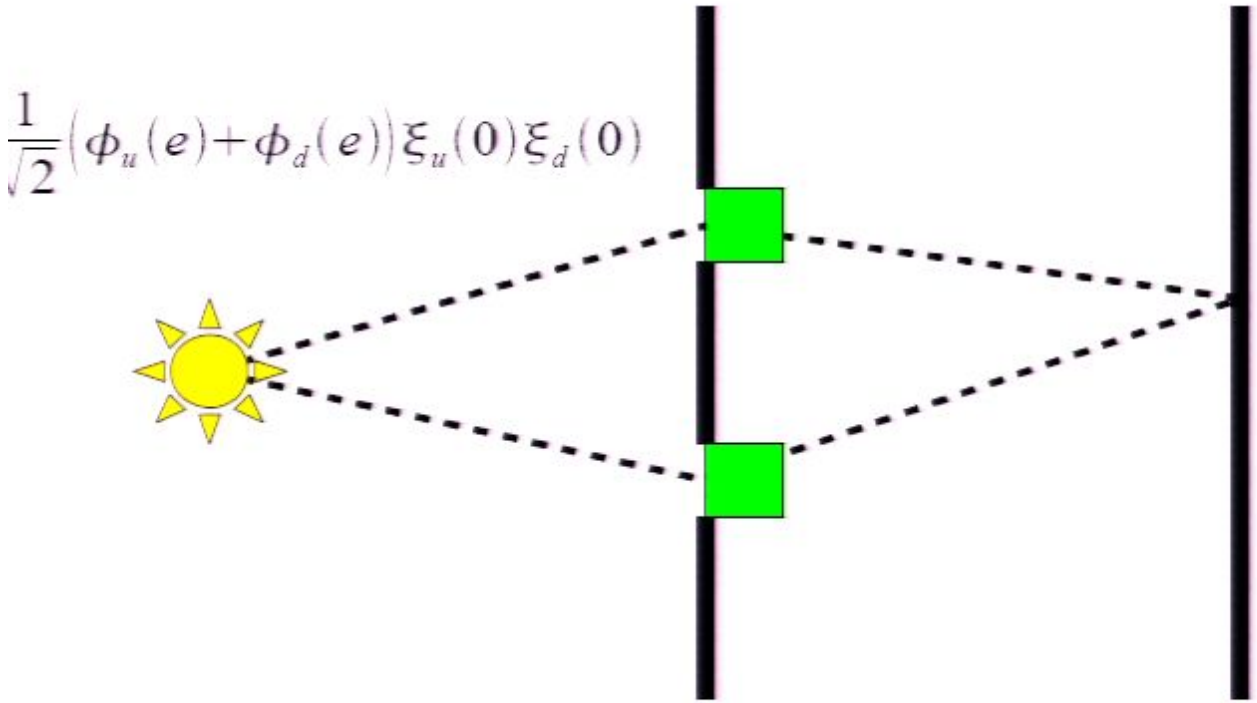
$$\rightarrow \frac{1}{\sqrt{2}}\phi_u(g)$$

$$\frac{1}{\sqrt{2}}\left(\phi_u(e) - \phi_d(e)\right)\xi_u(0)\xi_d(0)$$

$$\rightarrow \frac{1}{\sqrt{2}}\phi_u(g)\xi_u(1)\xi_d(0)$$


$\frac{1}{\sqrt{2}}(\phi_u(e)\tau - \phi_d(e))\xi_u(0)\xi_d(0)$
$\rightarrow \frac{1}{\sqrt{2}}(\phi_u(g)\xi_u(1)\xi_d(0) + \phi_d(g)\xi_u(0)\xi_d(1))$

Quantum phenomena : interferometry

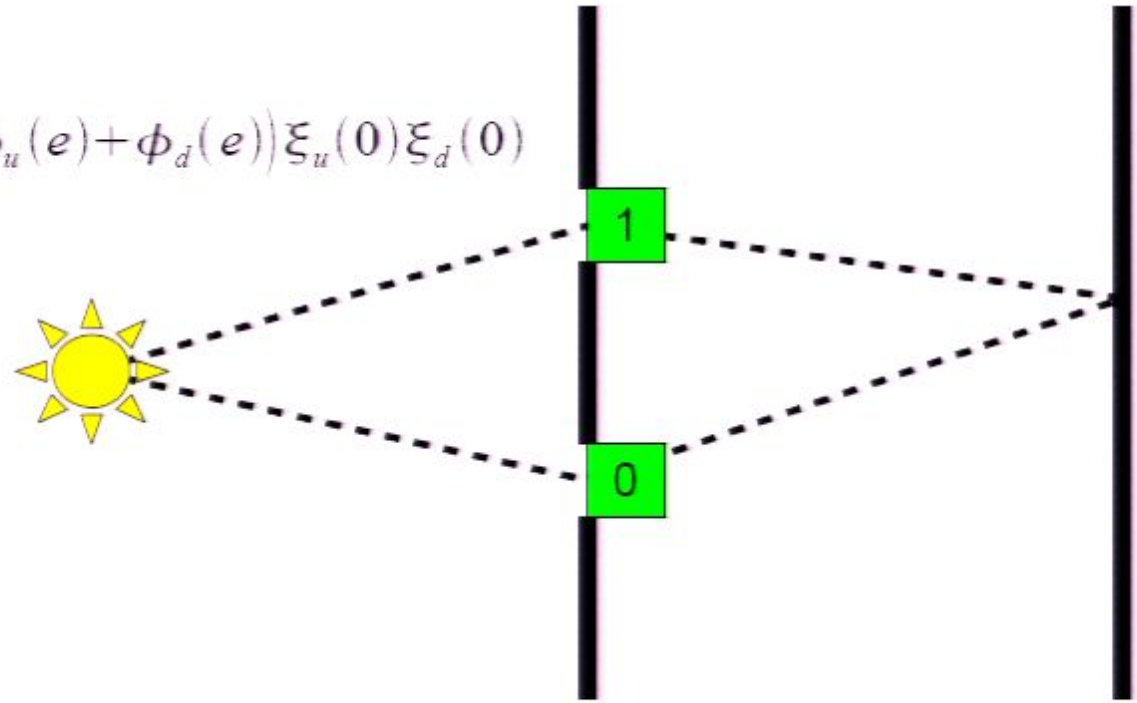


$\psi(e)\xi(0) \quad \psi(g)\xi(1)$

Optical QED Cavity

$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)$$

Quantum phenomena : interferometry



$$\frac{1}{\sqrt{2}}\left(\phi_u(e)+\phi_d(e)\right)\xi_u(0)\xi_d(0)$$

$$P(\xi_u(1)\xi_d(0))=\frac{1}{2}$$

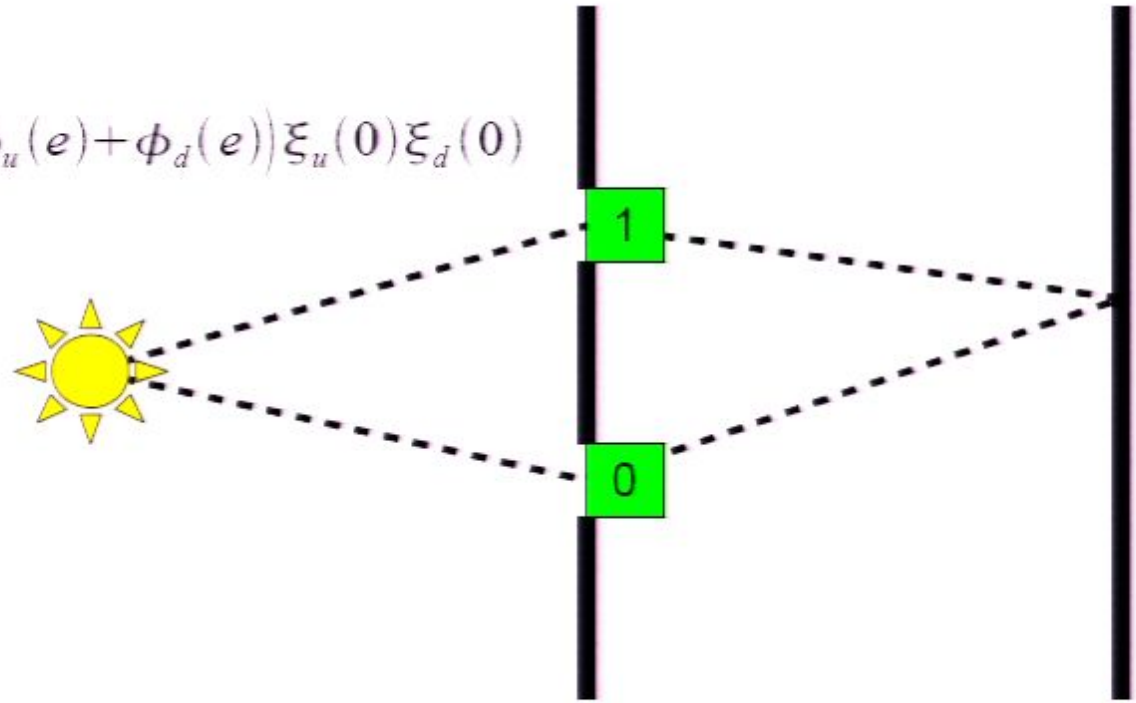
$$\phi_u(g)\xi_u(1)\xi_d(0)$$

$$\psi(e)\xi(0) \quad \psi(g)\xi(1)$$

Optical QED Cavity

$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)$$

Quantum phenomena : interferometry



$$\frac{1}{\sqrt{2}}\left(\phi_u(e)+\phi_d(e)\right)\xi_u(0)\xi_d(0)$$

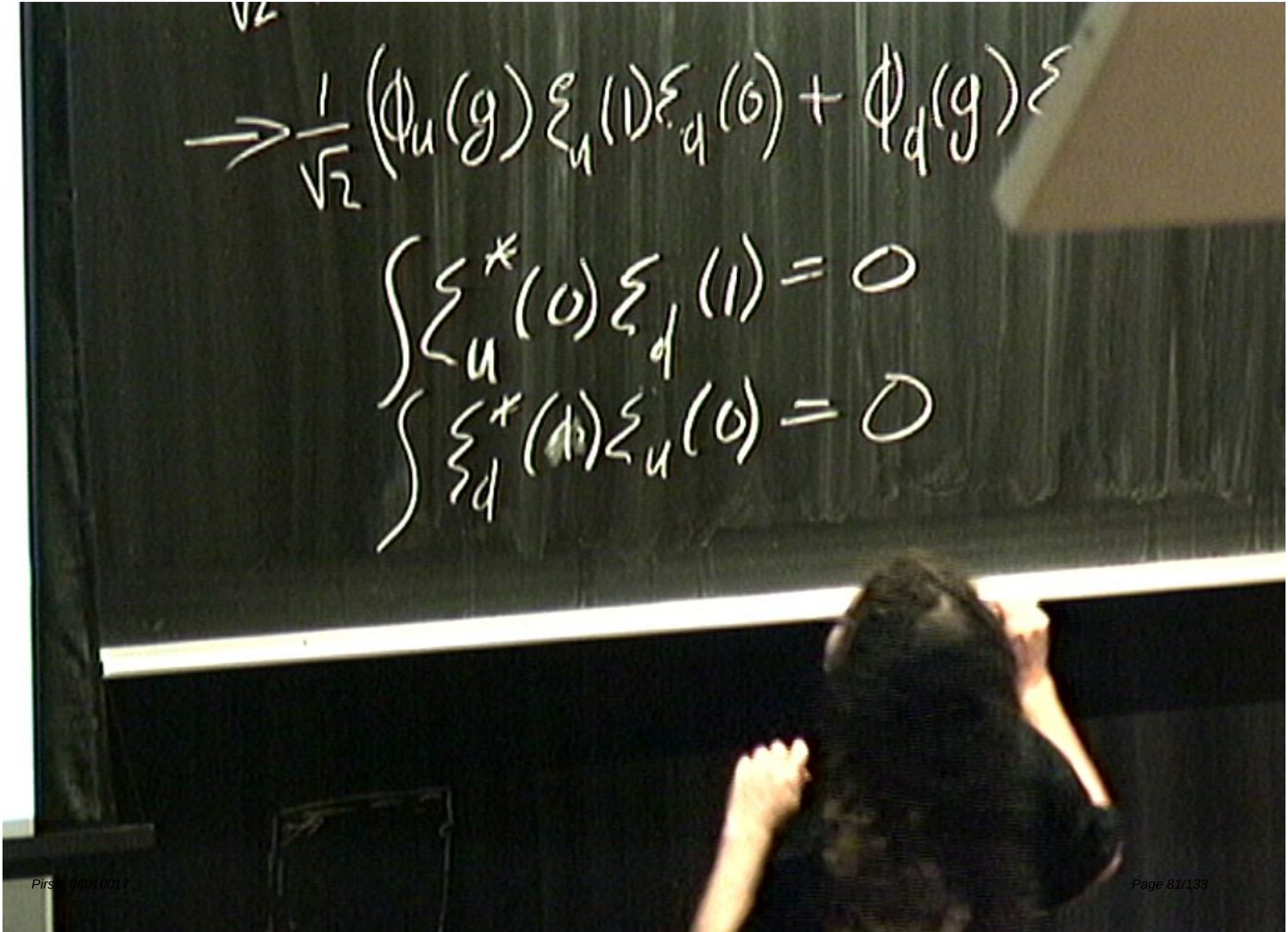
$$P(\xi_u(1)\xi_d(0))=\frac{1}{2}$$

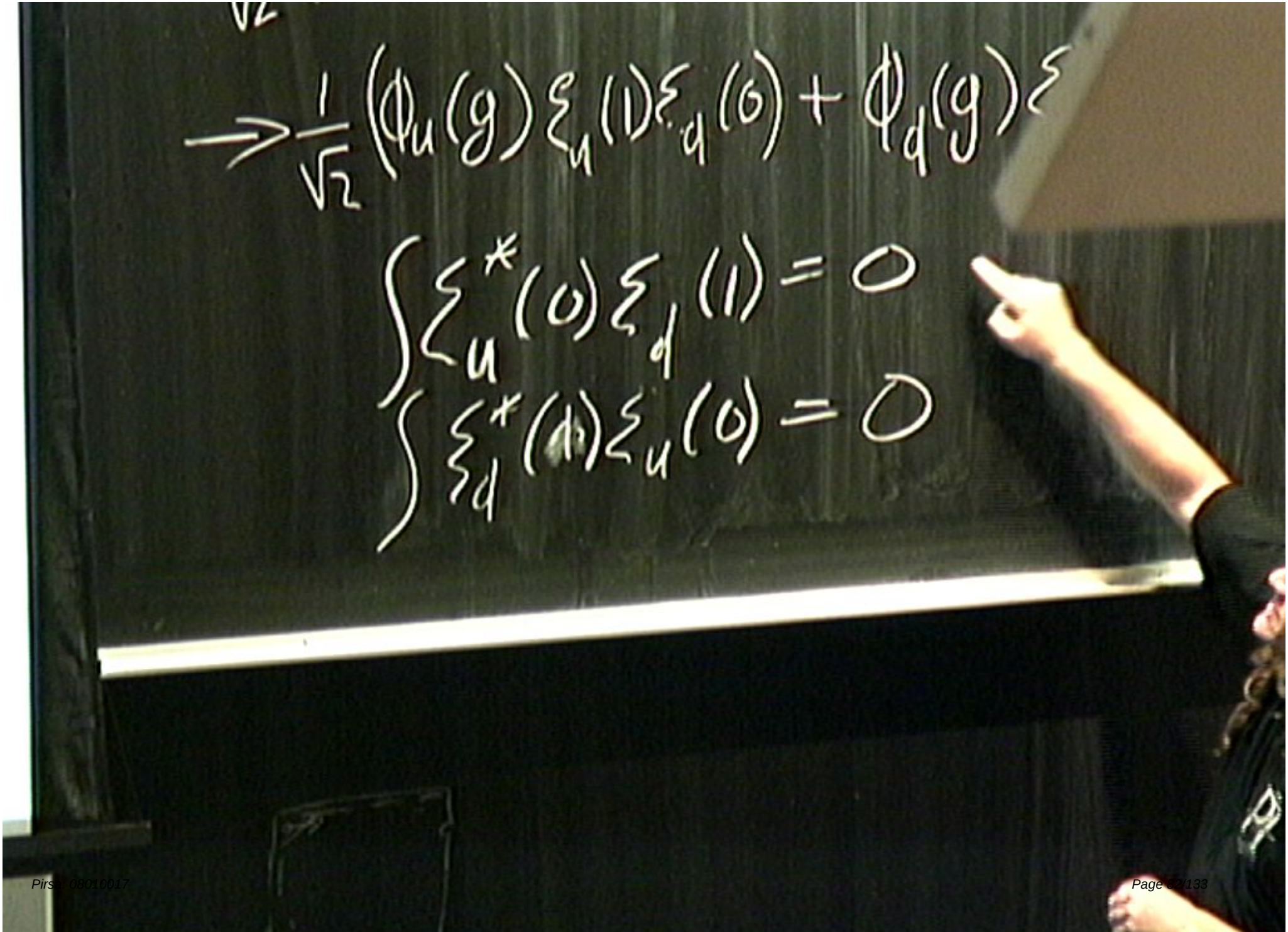
$$\phi_u(g)\xi_u(1)\xi_d(0)$$

$$\psi(e)\xi(0) \quad \psi(g)\xi(1)$$

Optical QED Cavity

$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)$$

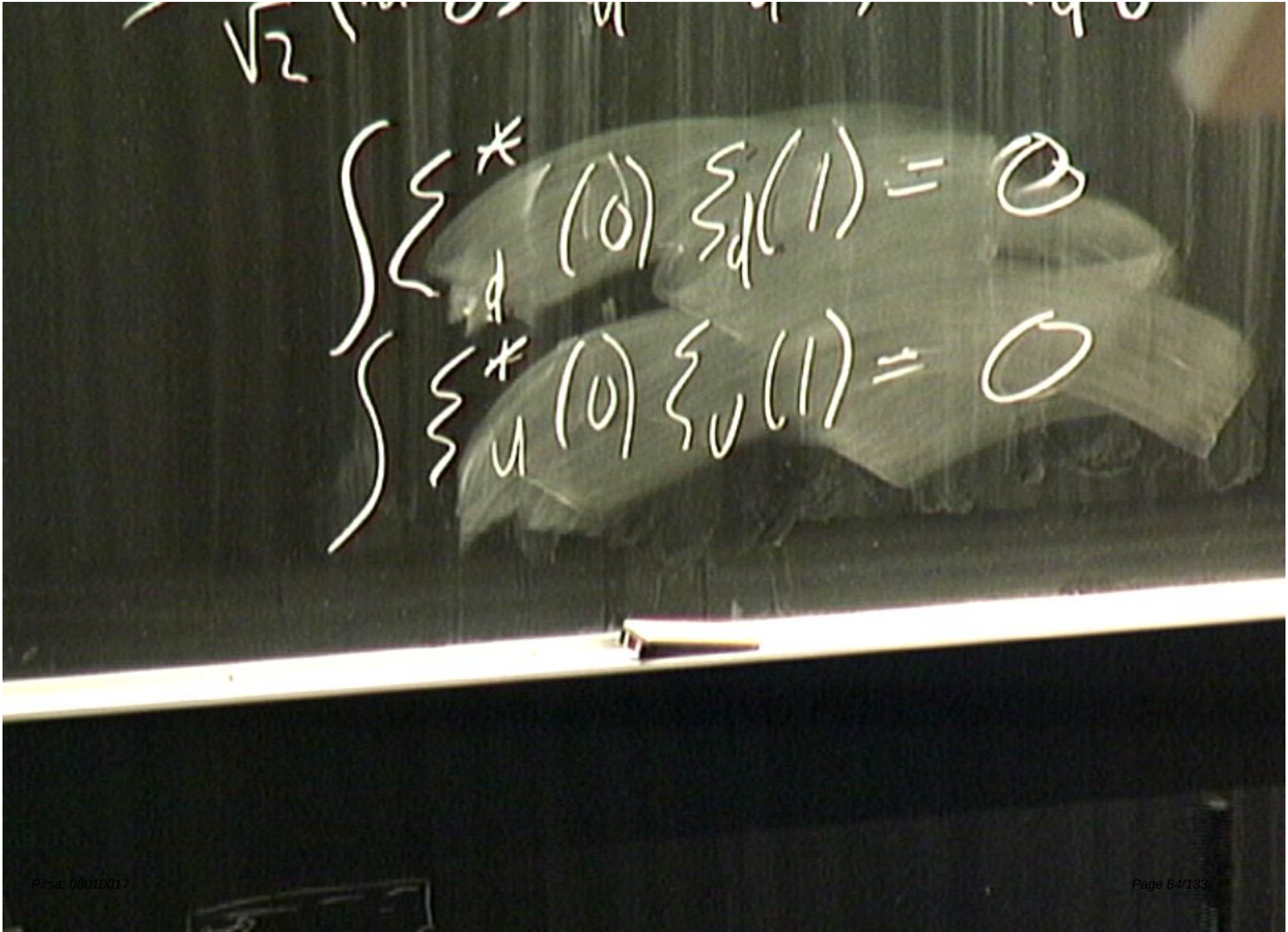

$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0) + \phi_d(g)\xi\right.$
$\int \xi_u^*(0)\xi_d(1) = 0$
$\int \xi_d^*(1)\xi_u(0) = 0$


$\frac{1}{\sqrt{2}}(\phi_u(g)\xi_u(1)\xi_d(0) + \phi_d(g)\xi$
$\int \xi_u^*(0)\xi_d(1) = 0$
$\int \xi_d^*(1)\xi_u(0) = 0$

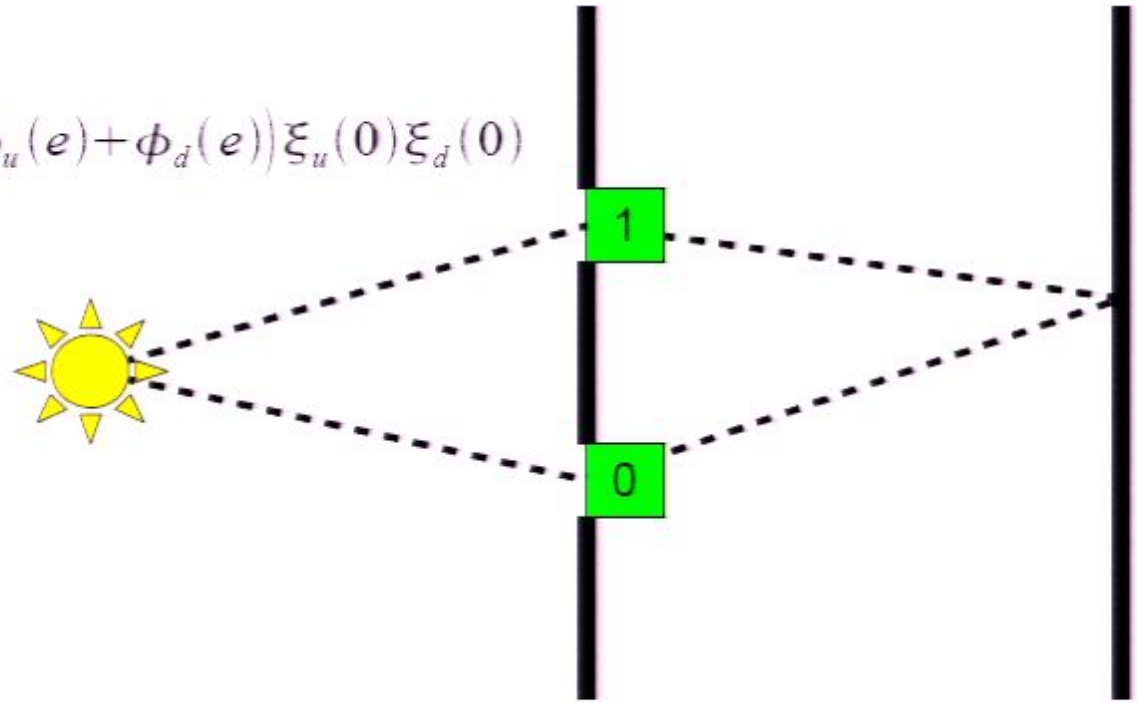
$$\rightarrow \frac{1}{\sqrt{2}}\left(\Phi_u(g)\,\xi_u(1)\xi_d(2) + \Phi_d(g)\right.$$

$$\int \xi_u^*(1)\,\xi_d(1) = 0$$

$$\int \xi_d^*(1)\,\xi_u(1) = 0$$


$\sqrt{2}$
$\xi_d^*(0)\,\xi_d(1) = 0$
$\xi_u^*(0)\,\xi_u(1) = 0$

Quantum phenomena : interferometry



$$\frac{1}{\sqrt{2}}\left(\phi_u(e)+\phi_d(e)\right)\xi_u(0)\xi_d(0)$$

$$P(\xi_u(1)\xi_d(0))=\frac{1}{2}$$

$$\phi_u(g)\xi_u(1)\xi_d(0)$$

$$\psi(e)\xi(0) \quad \psi(g)\xi(1)$$

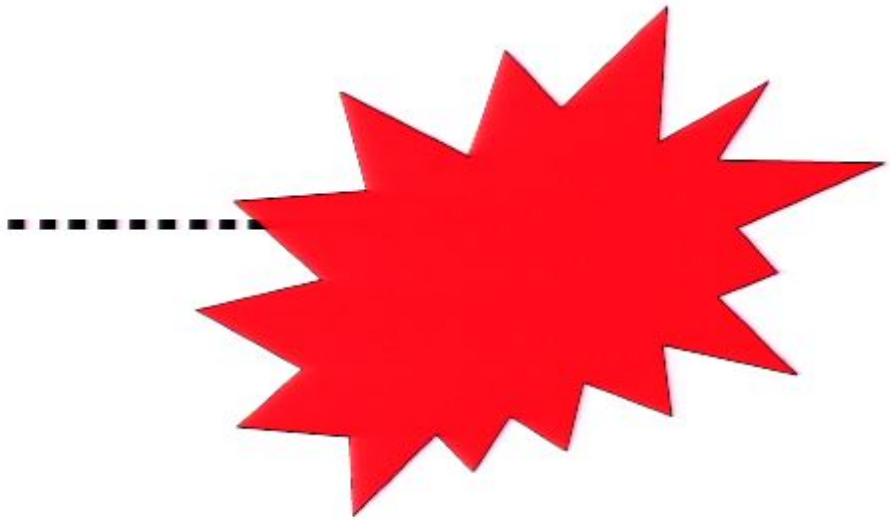
Optical QED Cavity

$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)$$

Quantum phenomena : interferometry

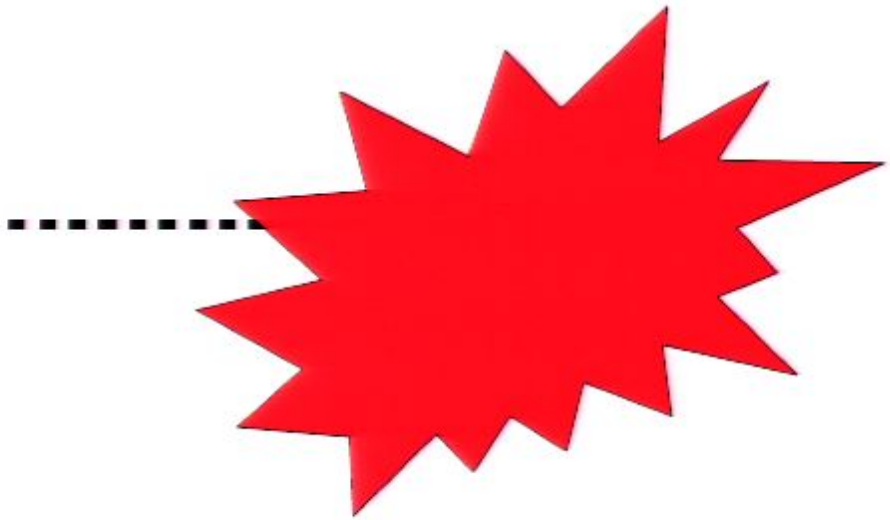
How to test a for dud bombs

Quantum phenomena : interferometry



... *without* destroying a good bomb?

Quantum phenomena : interferometry

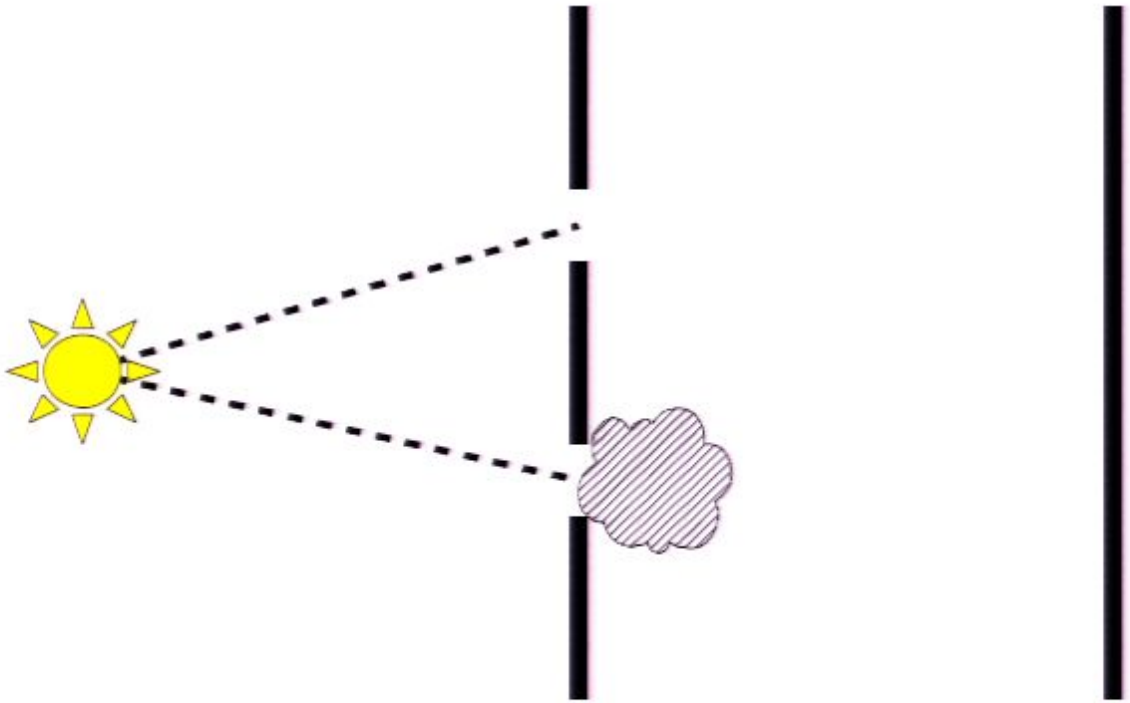


... *without* destroying a good bomb?

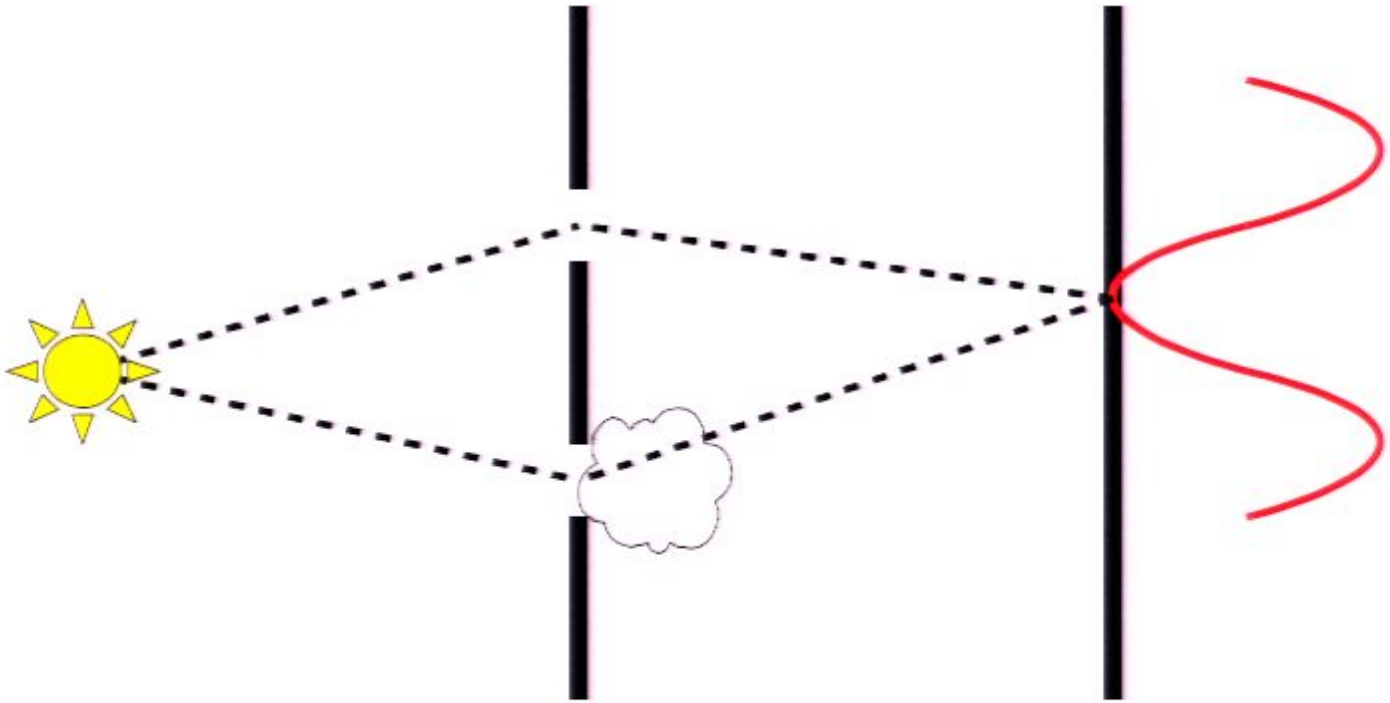
Quantum phenomena : interferometry

?

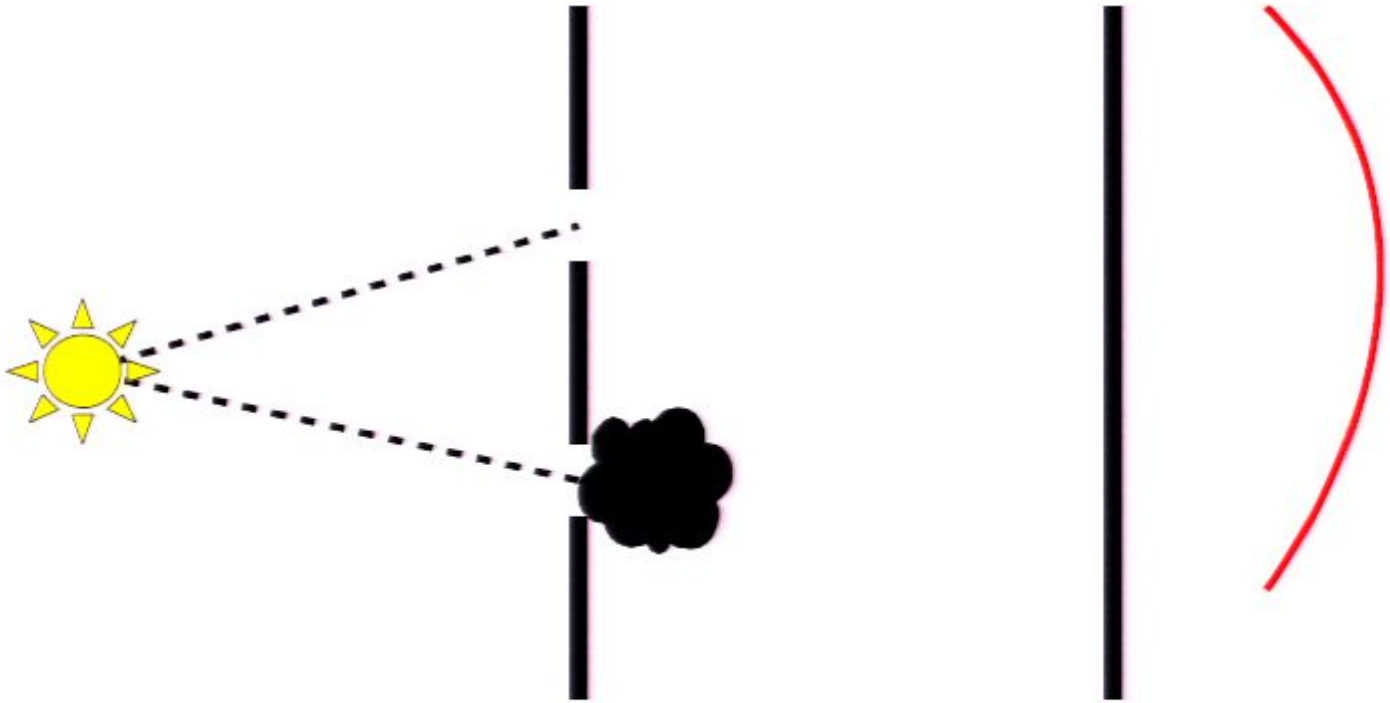
Quantum phenomena : interferometry



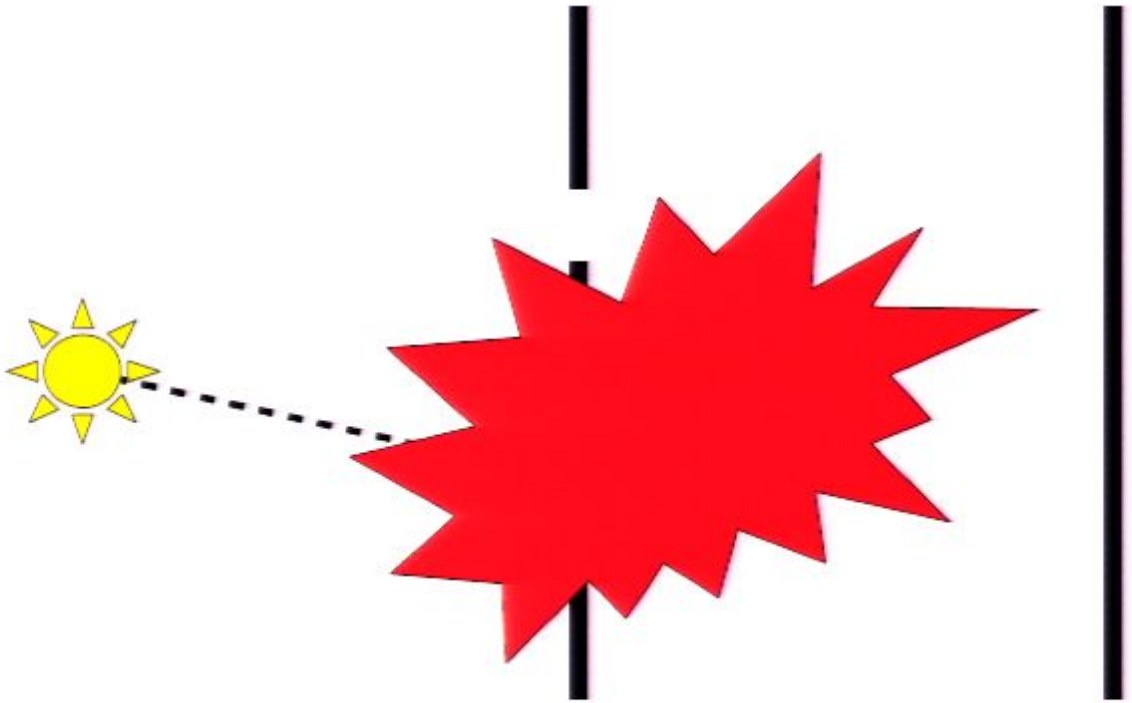
Quantum phenomena : interferometry



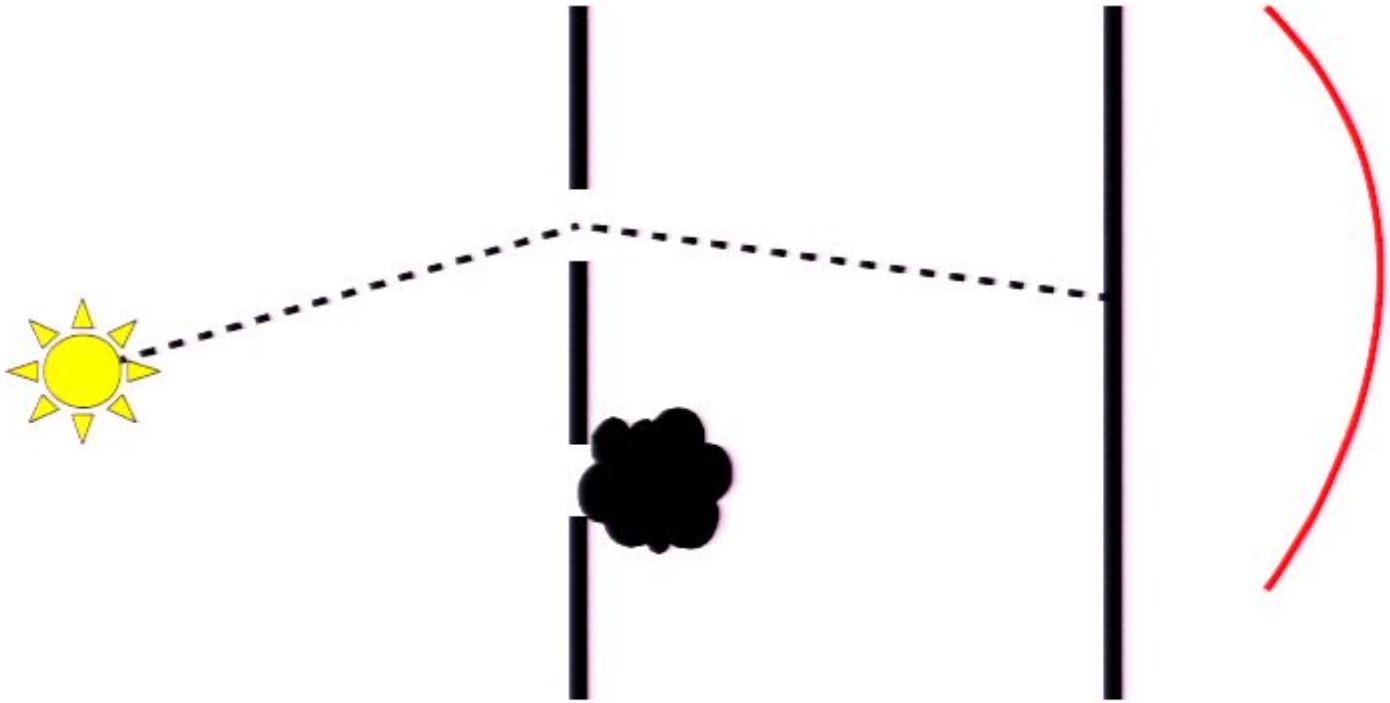
Quantum phenomena : interferometry



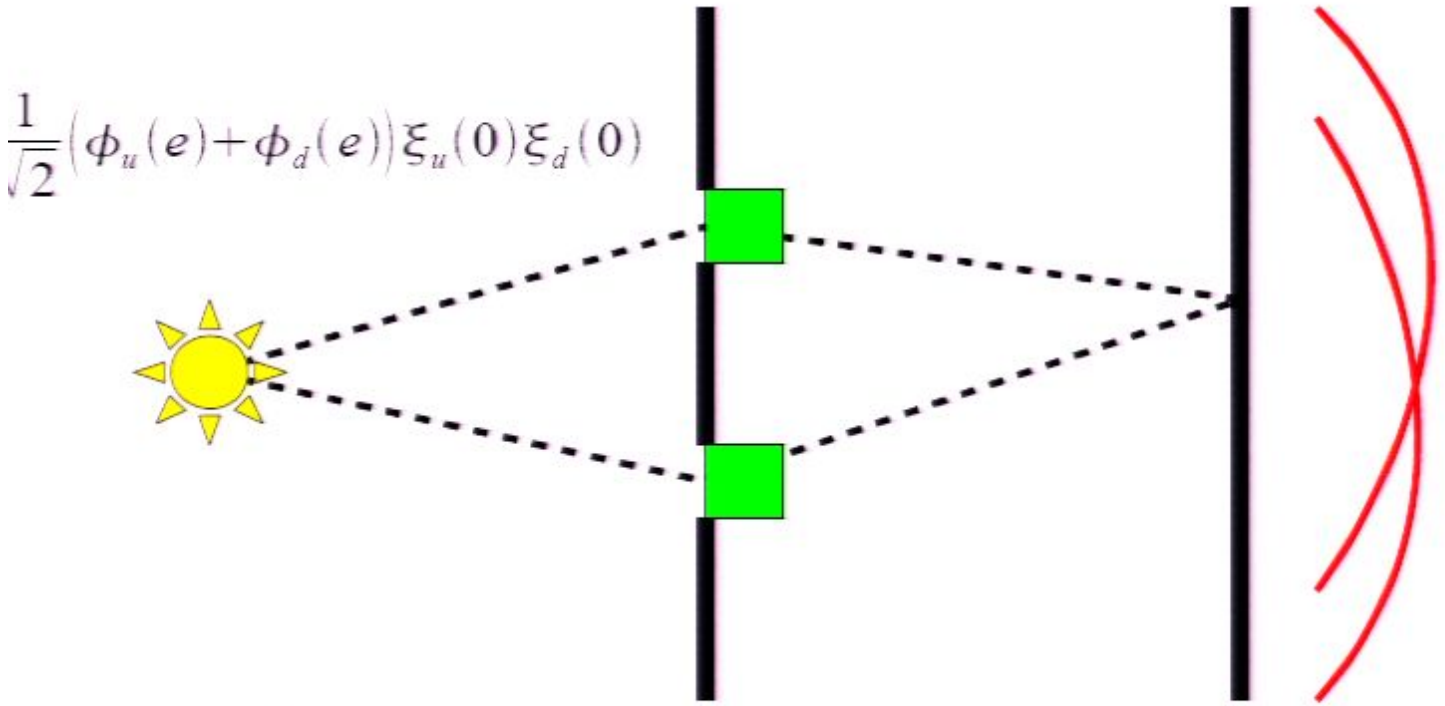
Quantum phenomena : interferometry



Quantum phenomena : interferometry



Quantum phenomena : interferometry



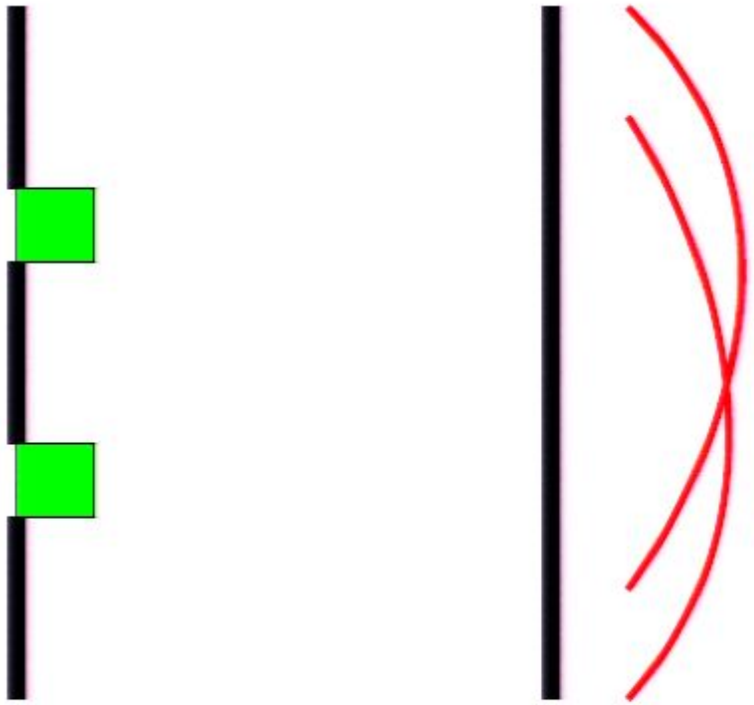
$\psi(e)\xi(0) \quad \psi(g)\xi(1)$

Optical QED Cavity

$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)$$

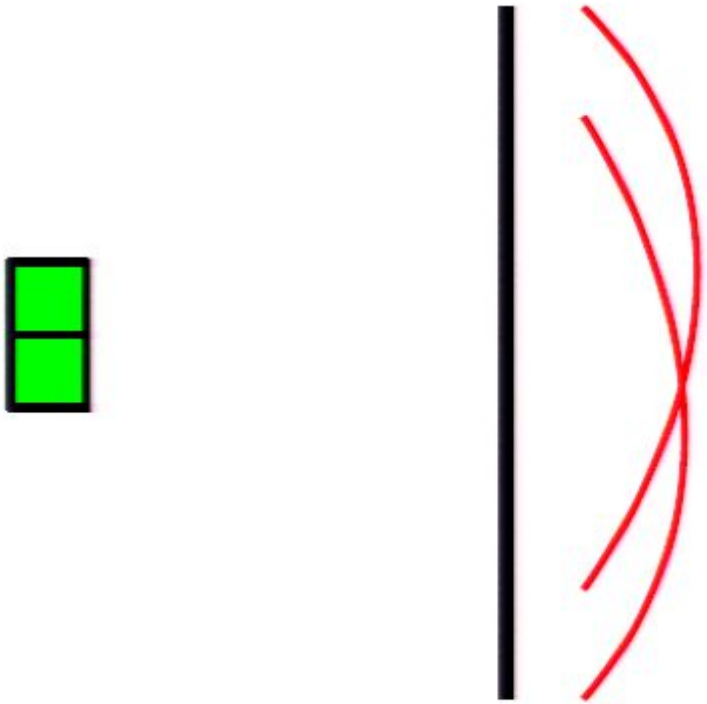
Quantum phenomena : interferometry

$$\frac{1}{\sqrt{2}}\left(\phi_u(e)+\phi_d(e)\right)\xi_u(0)\xi_d(0)$$



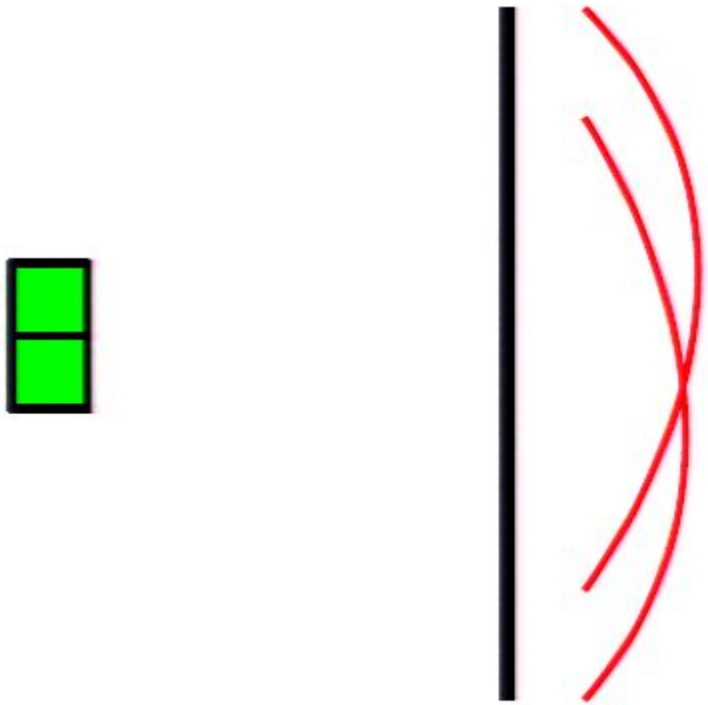
$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)$$

Quantum phenomena : interferometry



$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)$$

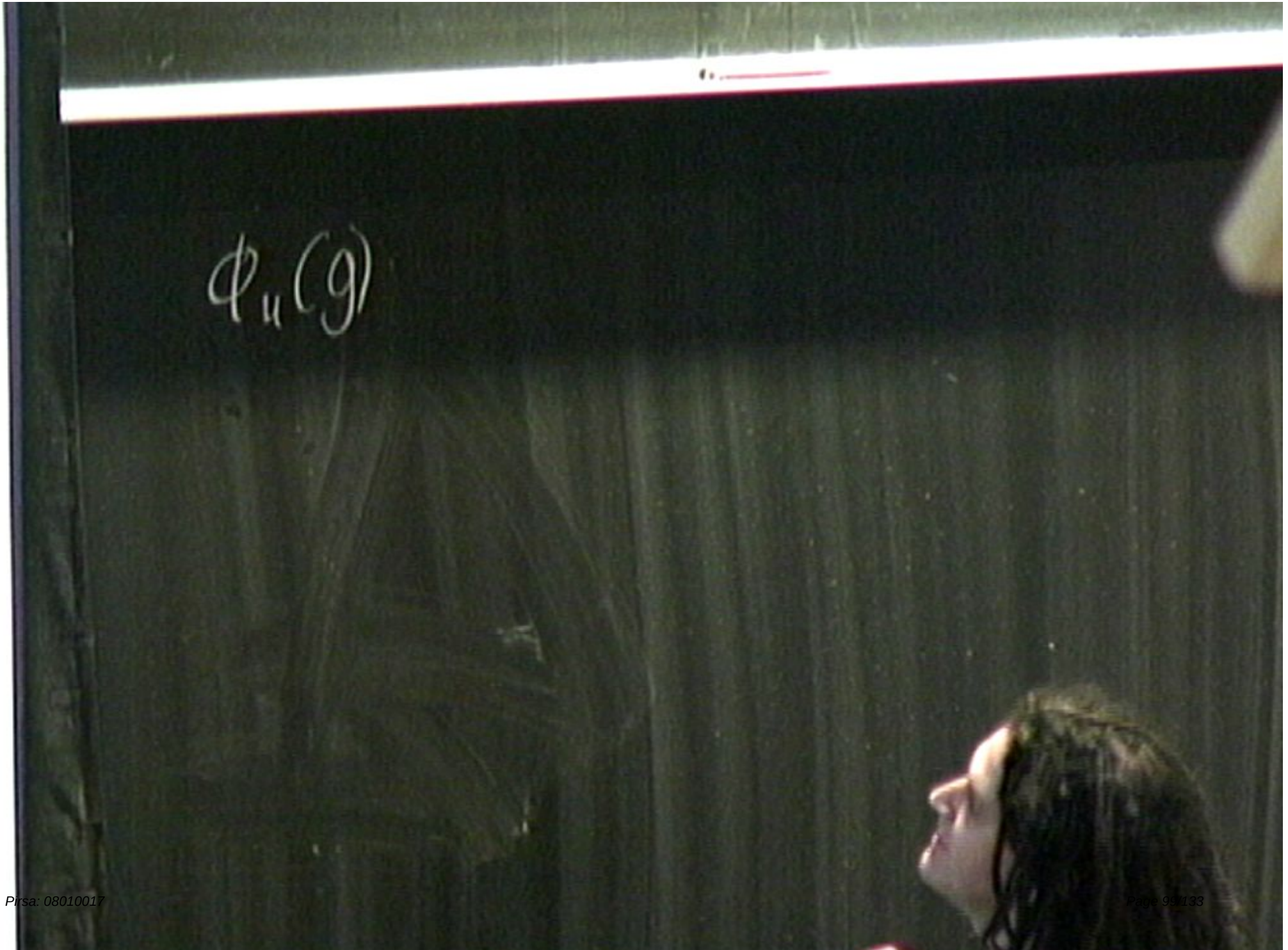
Quantum phenomena : interferometry

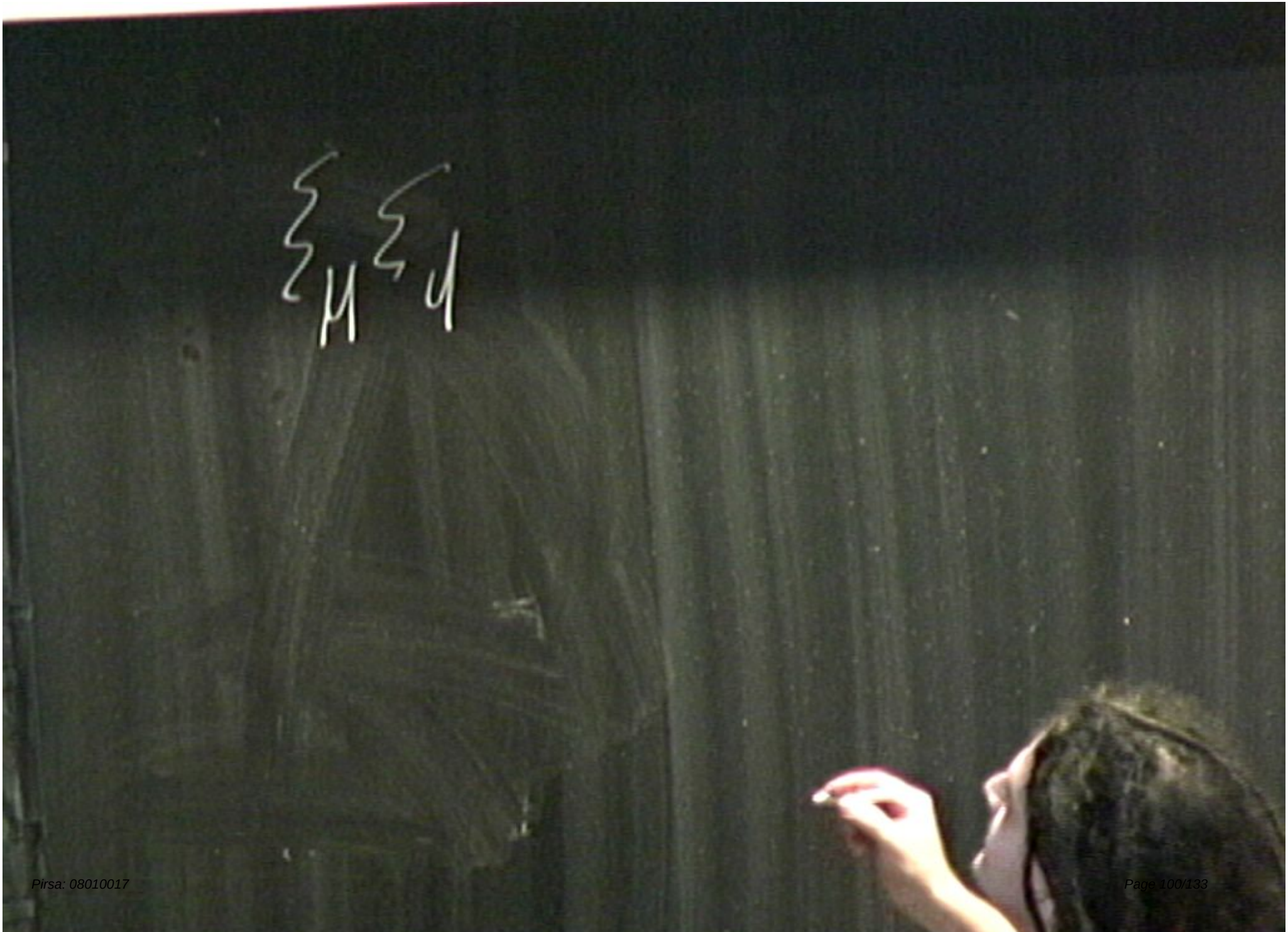


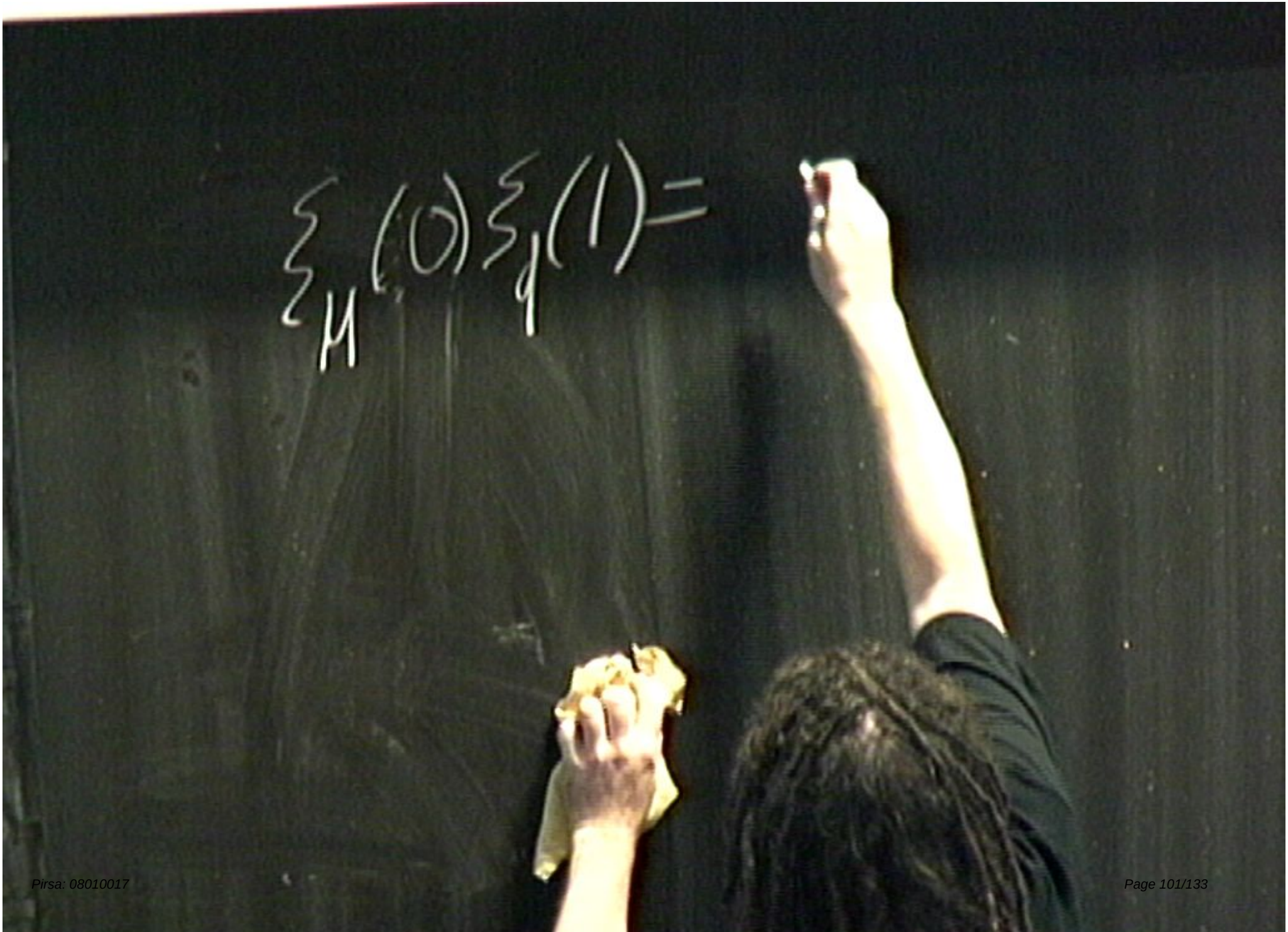
$$\xi_p = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) + \xi_u(0)\xi_d(1)\right)$$

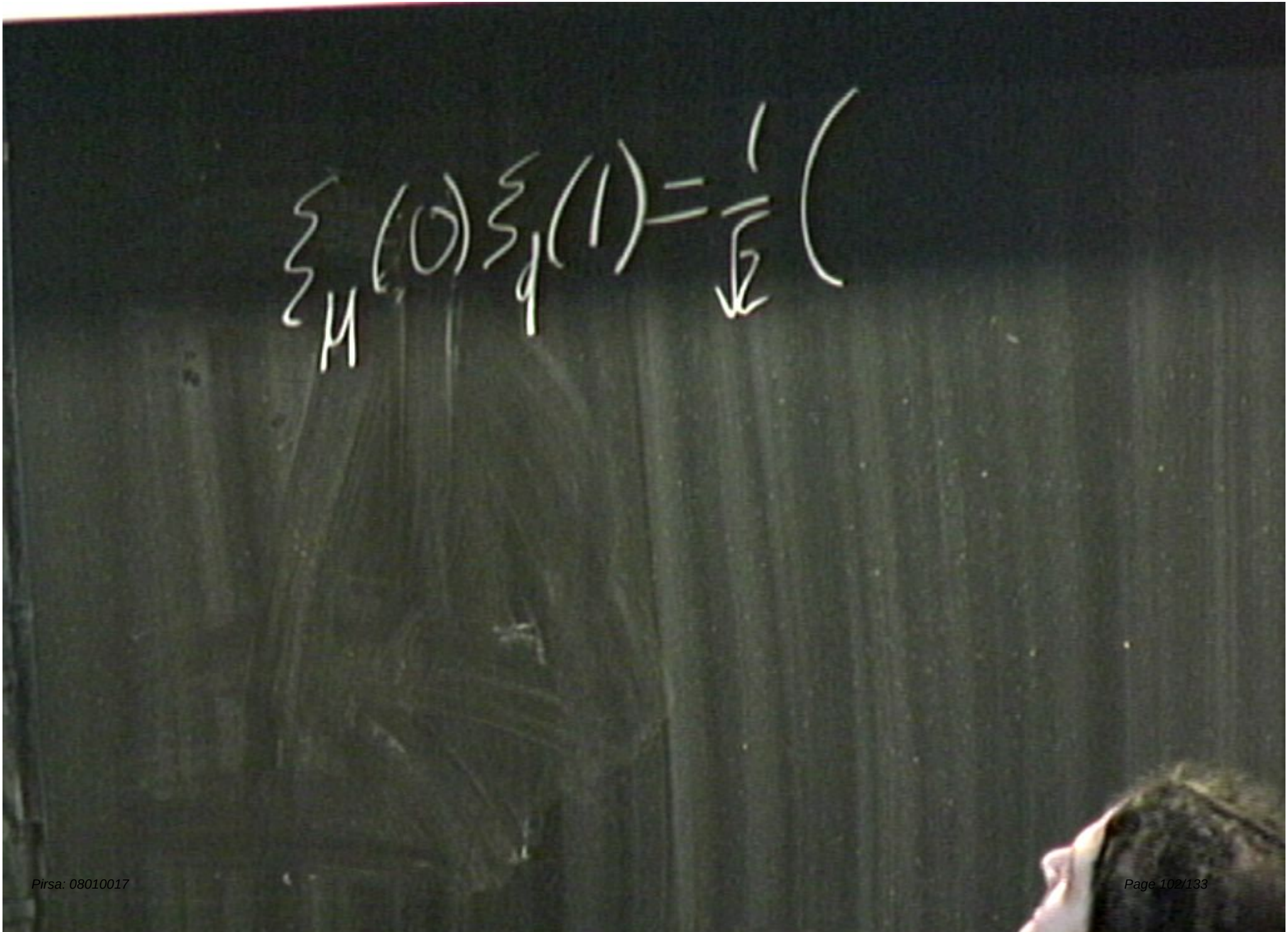
$$\xi_m = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) - \xi_u(0)\xi_d(1)\right)$$

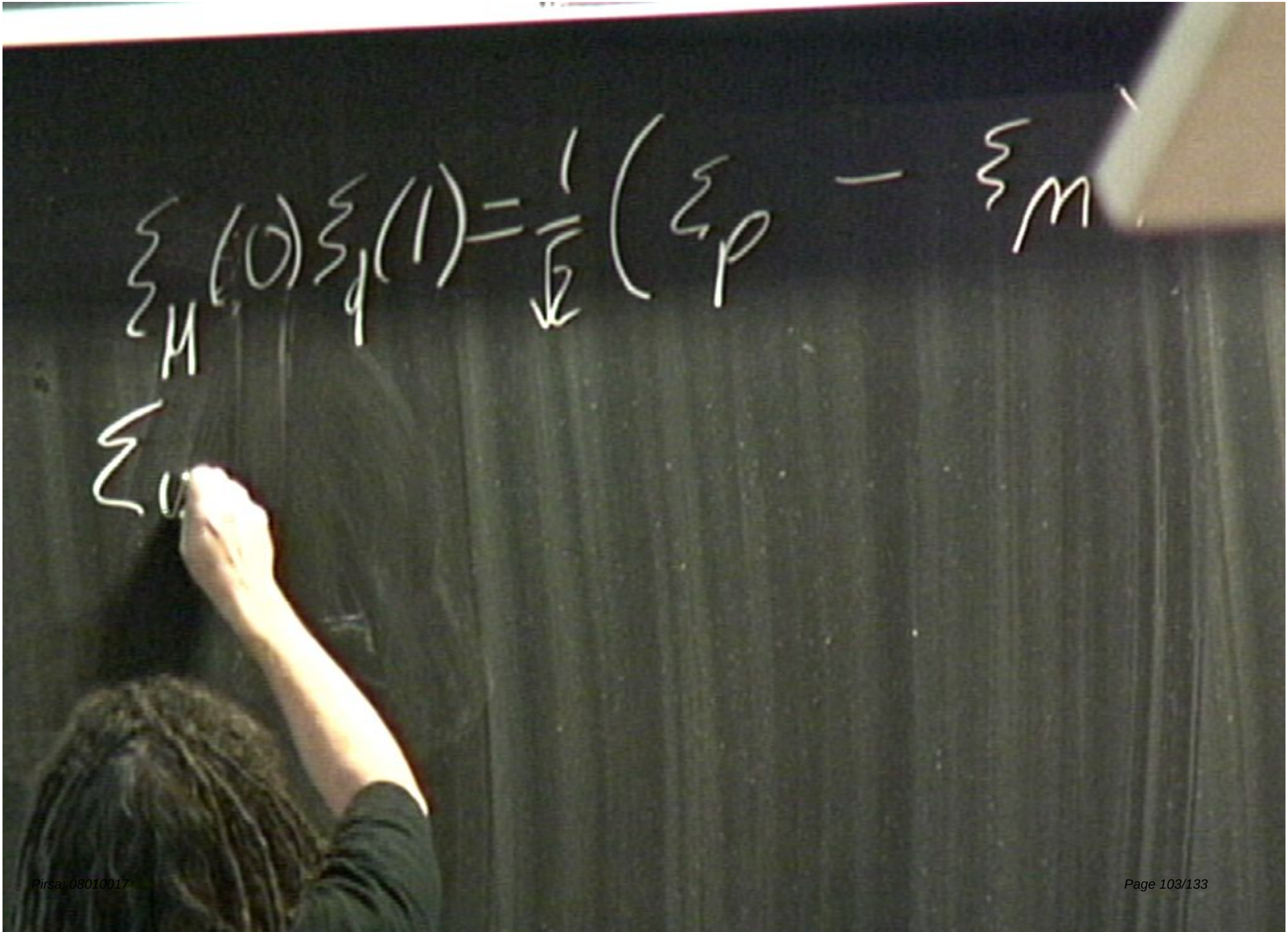
$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0) + \phi_d(g)\xi_u(0)\xi_d(1)\right)$$


$\Phi_4(9)$


$\xi_\mu \xi_\nu$

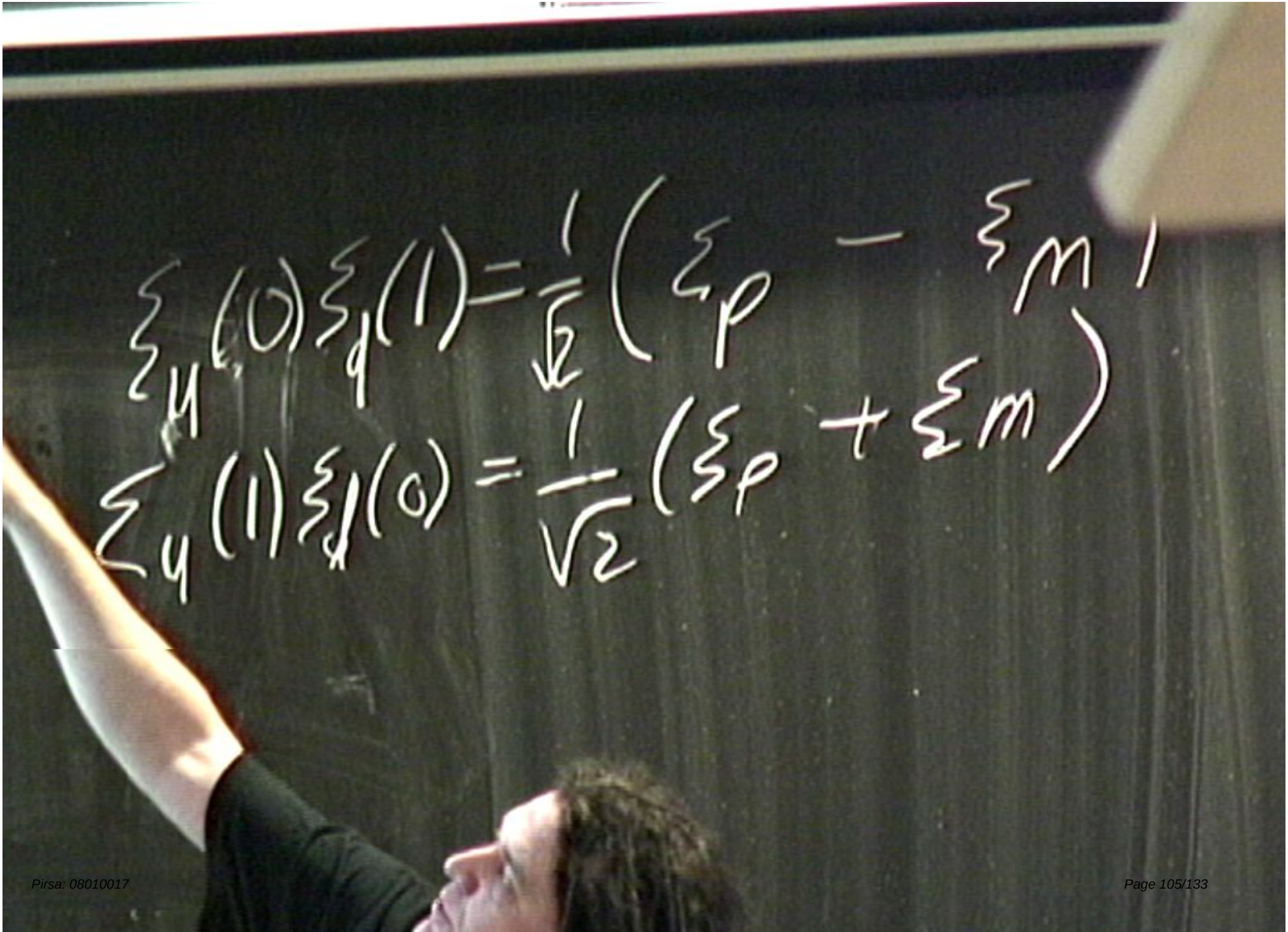

$\xi_\mu(;0)\xi_\nu(1)=$


$\xi_\mu(;0)\xi_q(1) = \frac{1}{\sqrt{2}}($


$\xi_\mu(0)\xi_q(1) = \frac{1}{\sqrt{2}}(\xi_p - \xi_m$
ξ_μ

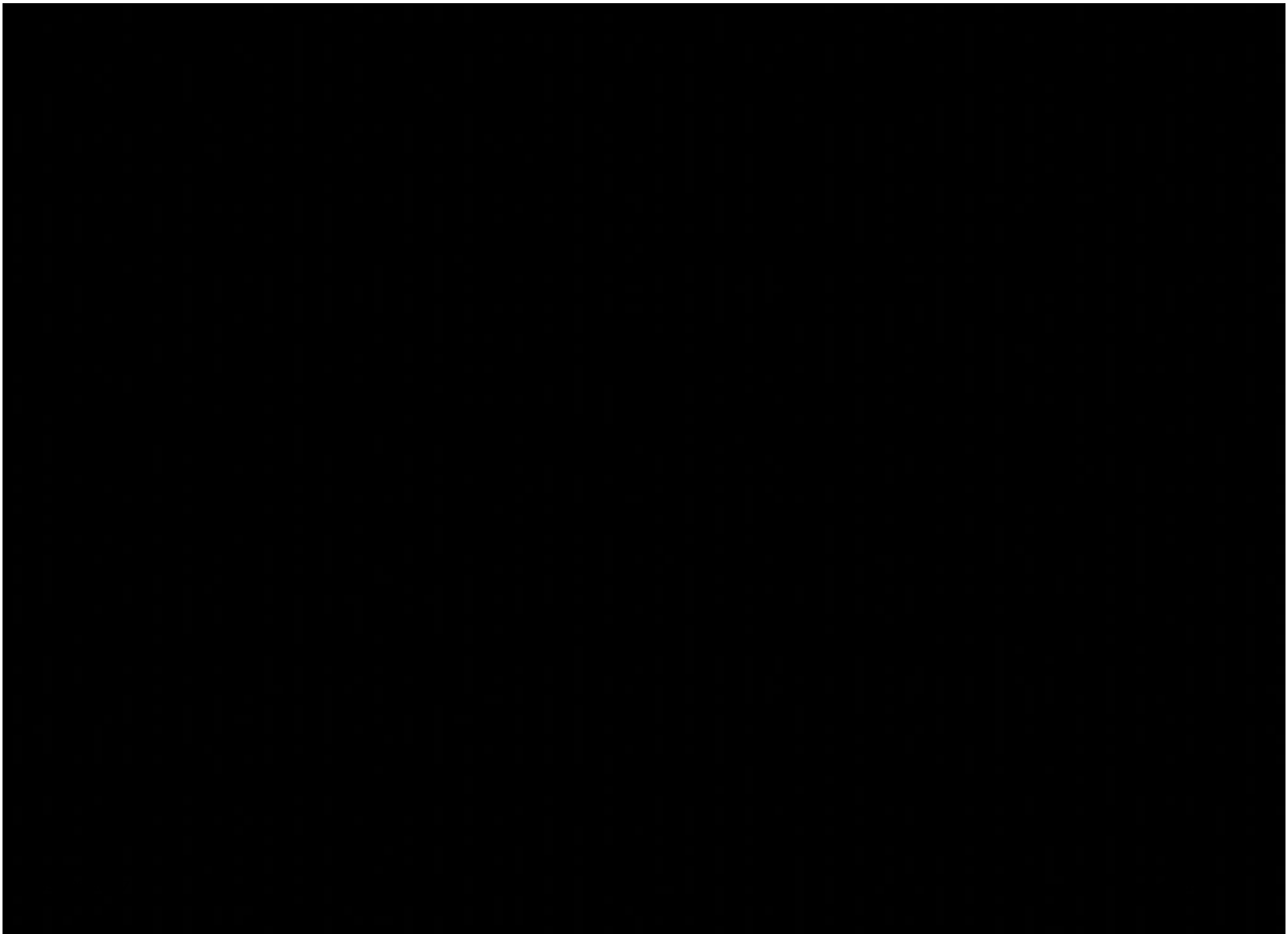
$$\xi_\mu(0)\xi_4(1) = \frac{1}{\sqrt{2}}(\xi_p - \xi_m)$$

$$\xi_4(1)\xi_4(0) = \frac{1}{\sqrt{2}}(\xi_p + \xi_m)$$

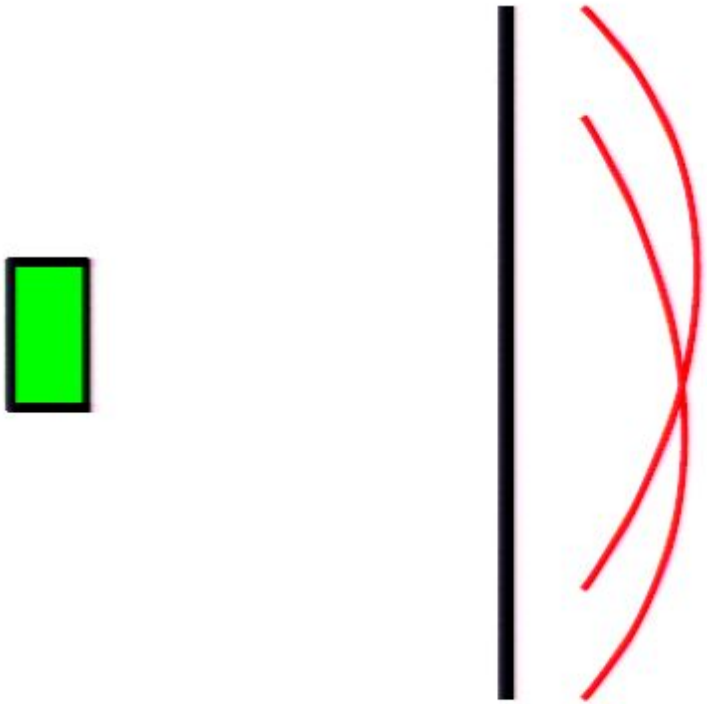

$\xi_\mu(0)\xi_4(1) = \frac{1}{\sqrt{2}}(\xi_p - \xi_m)$
$\xi_4(1)\xi_\mu(0) = \frac{1}{\sqrt{2}}(\xi_p + \xi_m)$

$$\xi_\mu(0)\xi_4(1) = \frac{1}{\sqrt{2}}(\xi_p - \xi_m)$$

$$\xi_4(1)\xi_4(0) = \frac{1}{\sqrt{2}}(\xi_p + \xi_m)$$



Quantum phenomena : interferometry

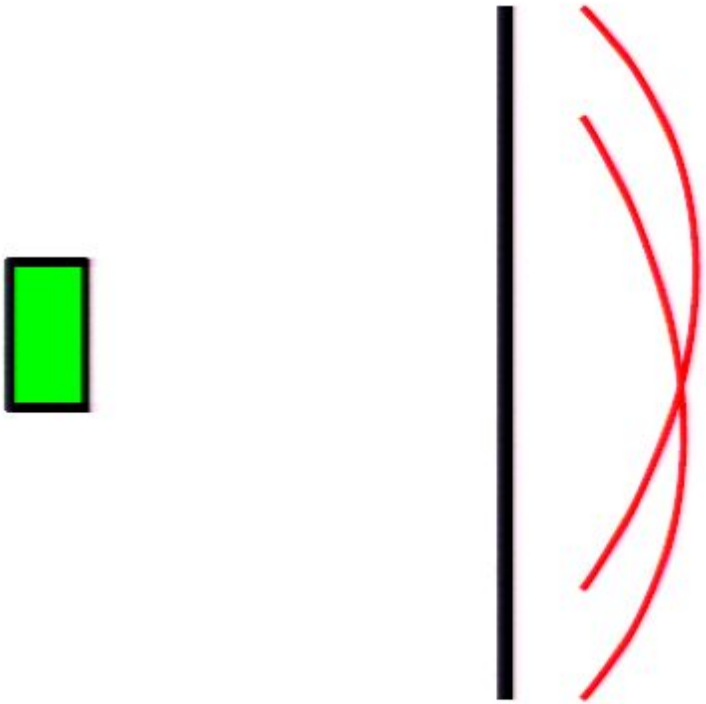


$$\xi_p = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) + \xi_u(0)\xi_d(1)\right)$$

$$\xi_m = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) - \xi_u(0)\xi_d(1)\right)$$

$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0) + \phi_d(g)\xi_u(0)\xi_d(1)\right) = \frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p + \frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry

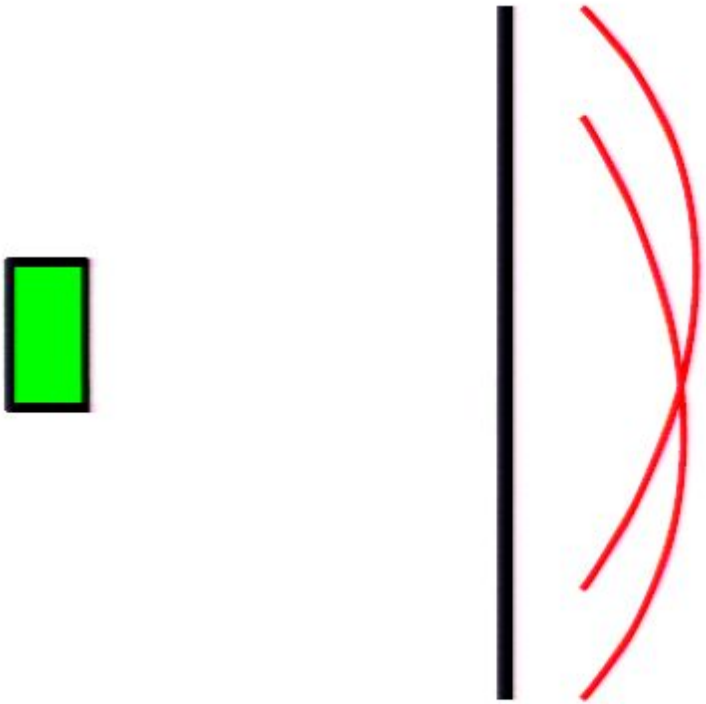


$$\xi_p = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) + \xi_u(0)\xi_d(1)\right)$$

$$\xi_m = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) - \xi_u(0)\xi_d(1)\right)$$

$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0) + \phi_d(g)\xi_u(0)\xi_d(1)\right) = \frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p + \frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry

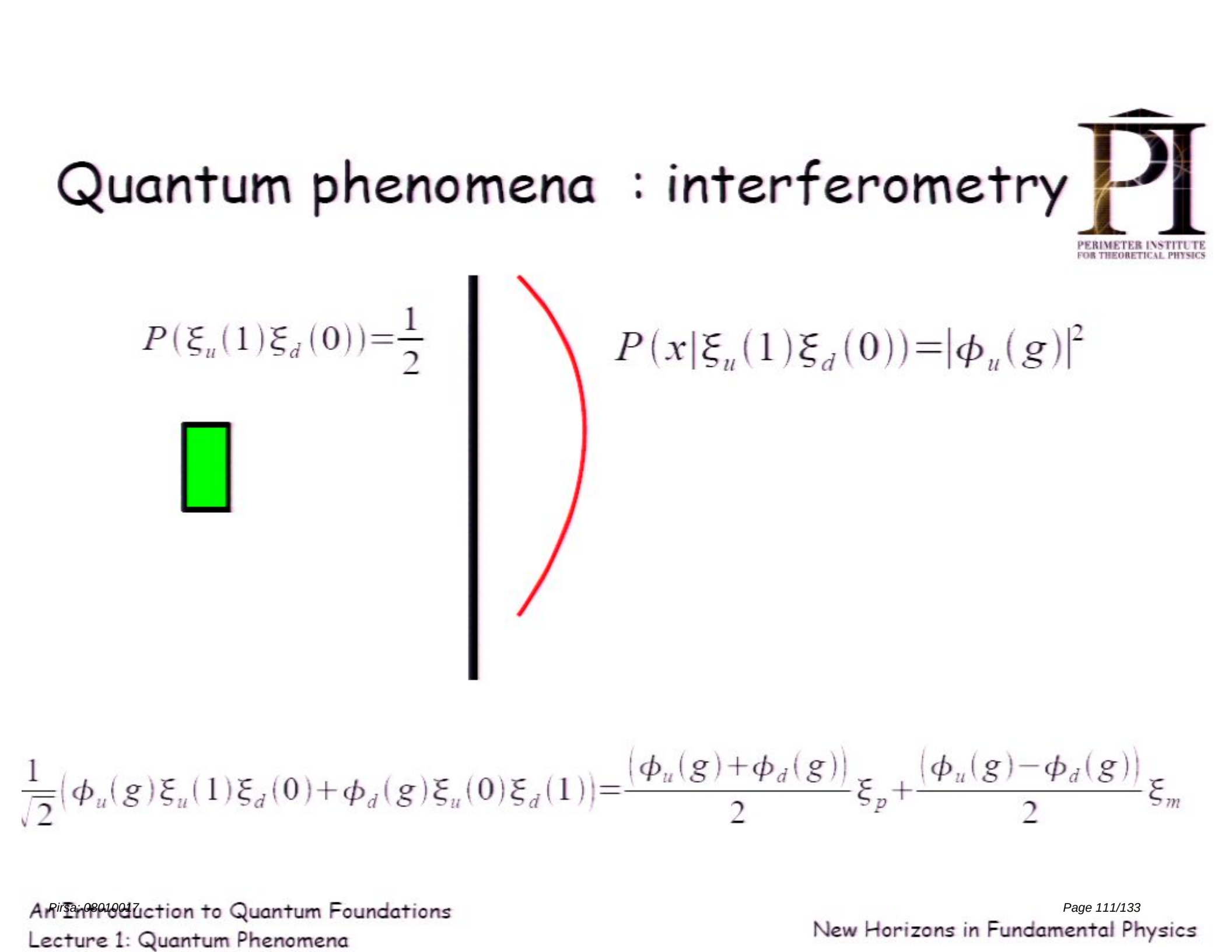


$$\xi_p = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) + \xi_u(0)\xi_d(1)\right)$$

$$\xi_m = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) - \xi_u(0)\xi_d(1)\right)$$

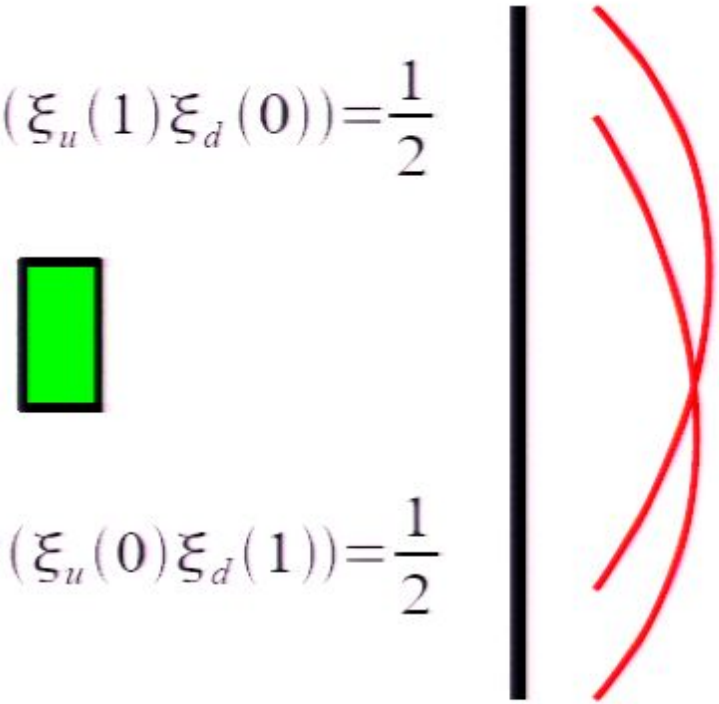
$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0) + \phi_d(g)\xi_u(0)\xi_d(1)\right) = \frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p + \frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry



$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)=\frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p+\frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry



$$P(\xi_u(1)\xi_d(0))=\frac{1}{2}$$

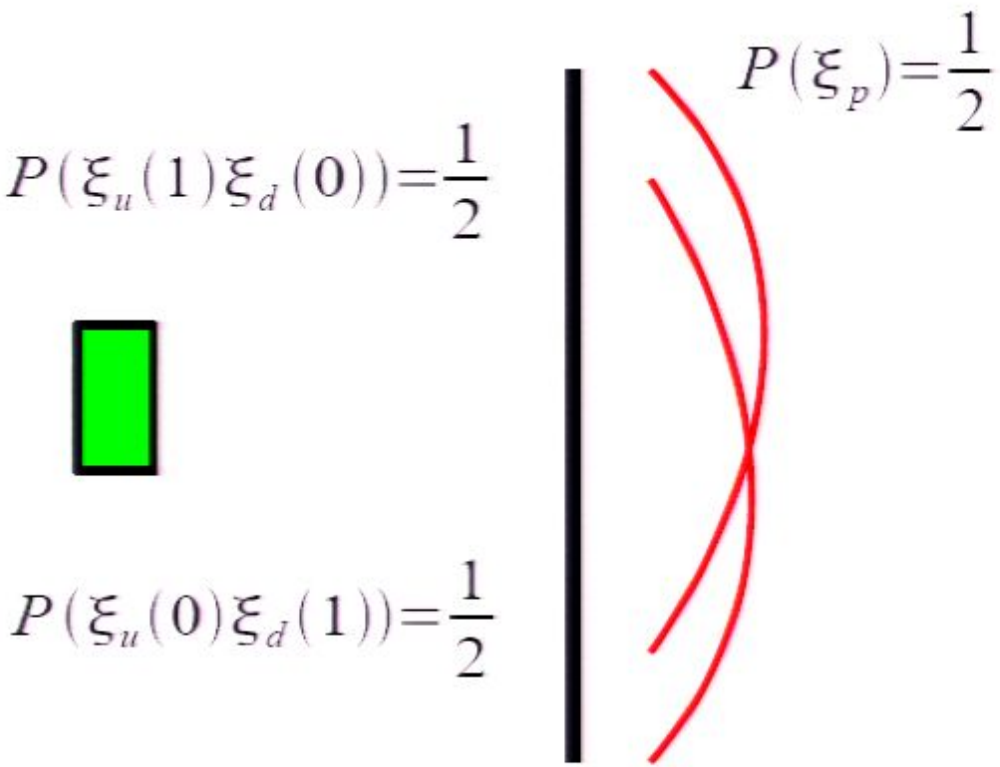
$$P(x|\xi_u(1)\xi_d(0))=|\phi_u(g)|^2$$

$$P(\xi_u(0)\xi_d(1))=\frac{1}{2}$$

$$P(x|\xi_u(0)\xi_d(1))=|\phi_d(g)|^2$$

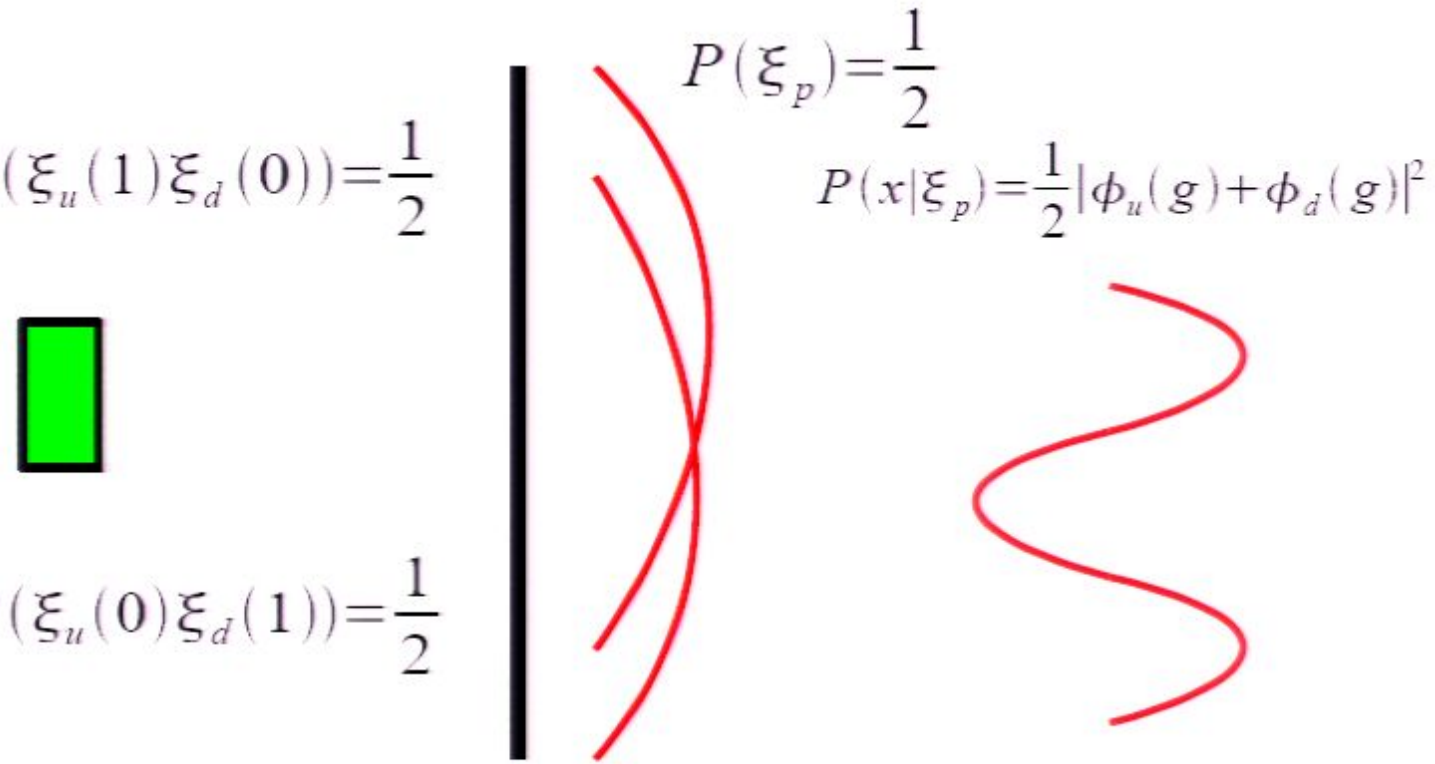
$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)=\frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p+\frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry



$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)=\frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p+\frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry



$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)=\frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p+\frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry

$$P(\xi_u(1)\xi_d(0))=\frac{1}{2}$$

$$P(\xi_u(0)\xi_d(1))=\frac{1}{2}$$

$$P(\xi_p)=\frac{1}{2}$$

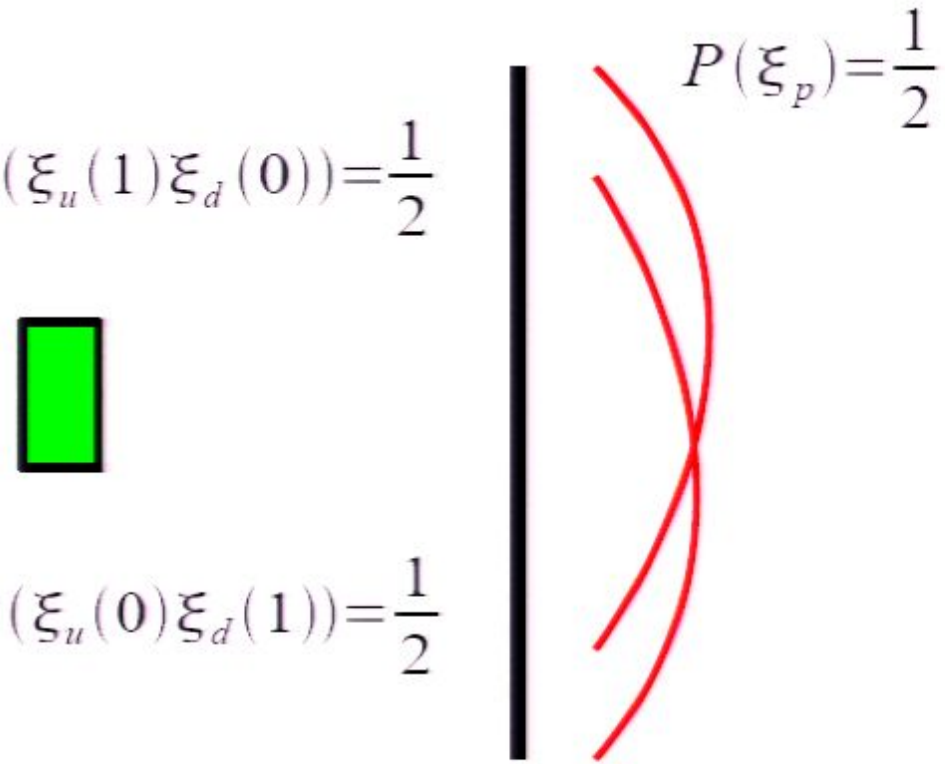
$$P(x|\xi_p)=\frac{1}{2}|\phi_u(g)+\phi_d(g)|^2$$

$$P(\xi_m)=\frac{1}{2}$$

$$P(x|\xi_m)=\frac{1}{2}|\phi_u(g)-\phi_d(g)|^2$$

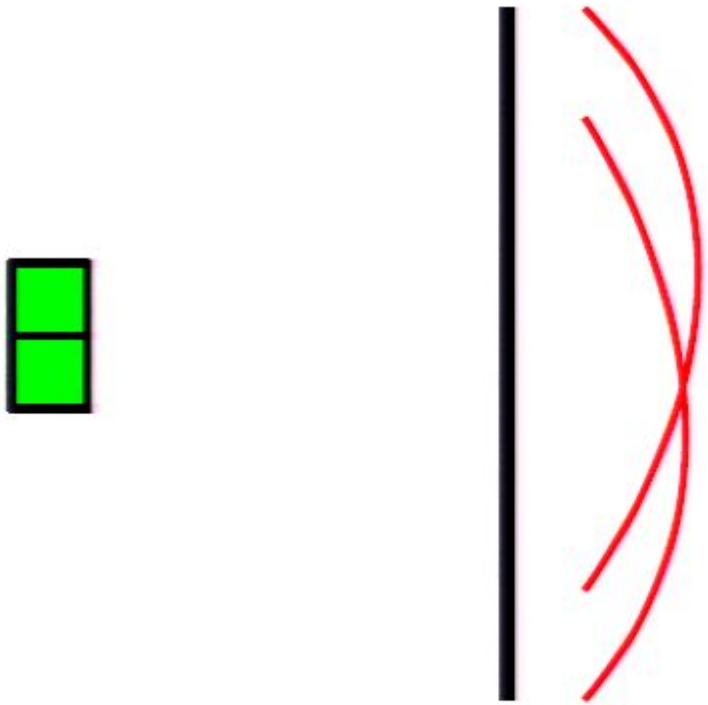
$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)=\frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p+\frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry



$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)=\frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p+\frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry

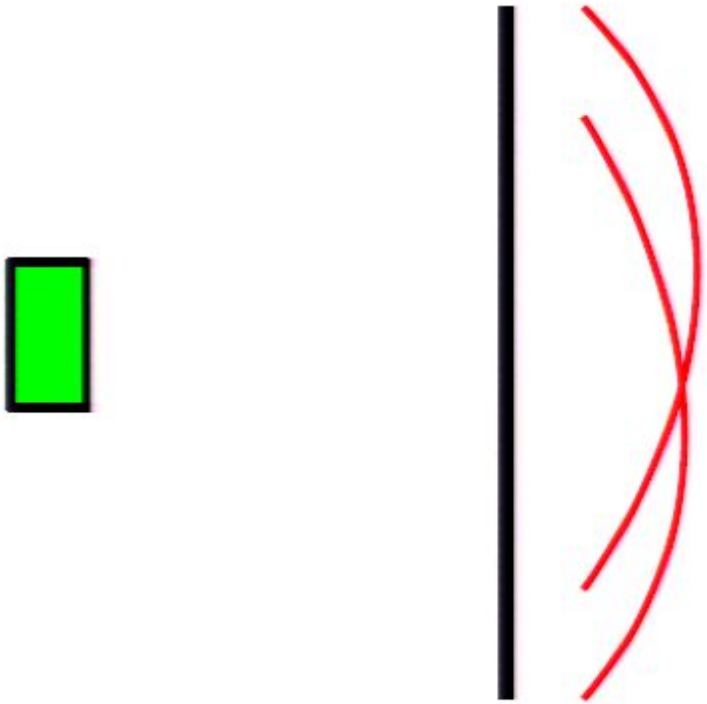


$$\xi_p = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) + \xi_u(0)\xi_d(1)\right)$$

$$\xi_m = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) - \xi_u(0)\xi_d(1)\right)$$

$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0) + \phi_d(g)\xi_u(0)\xi_d(1)\right)$$

Quantum phenomena : interferometry

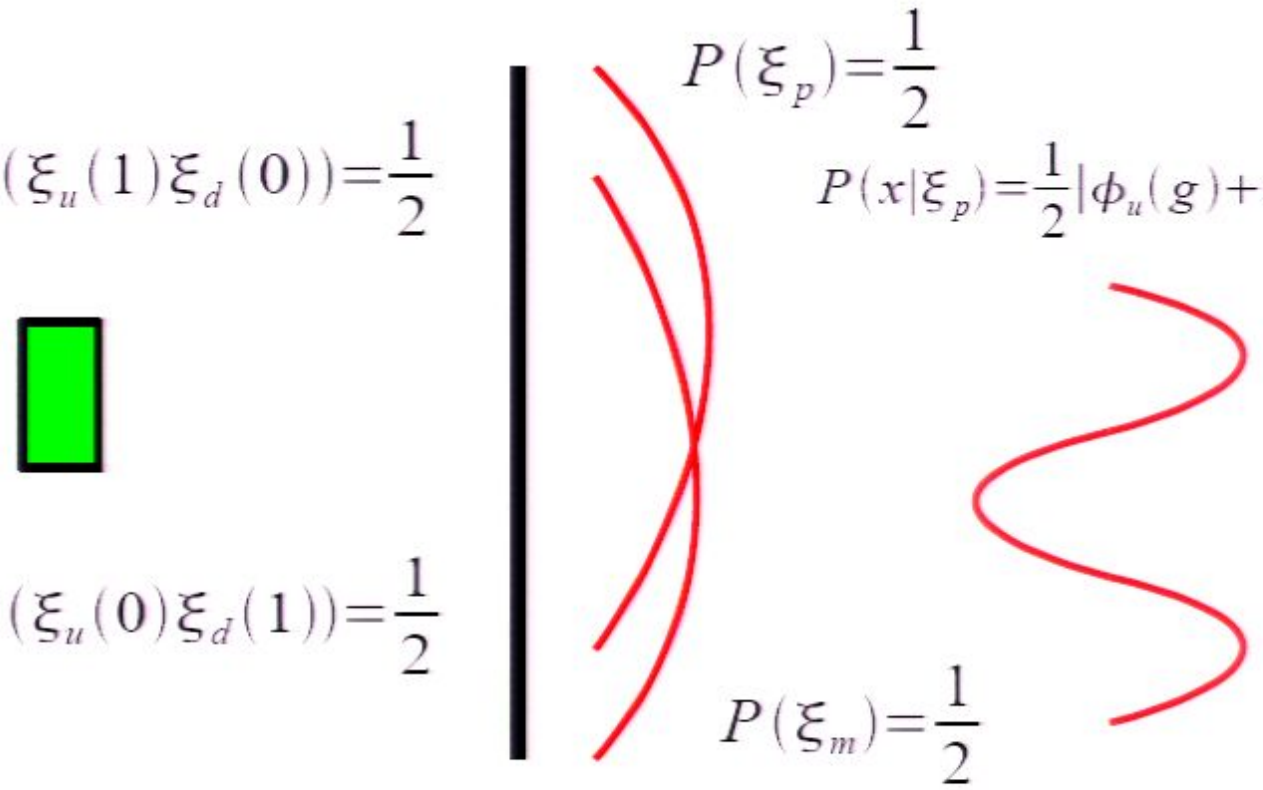


$$\xi_p = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) + \xi_u(0)\xi_d(1)\right)$$

$$\xi_m = \frac{1}{\sqrt{2}}\left(\xi_u(1)\xi_d(0) - \xi_u(0)\xi_d(1)\right)$$

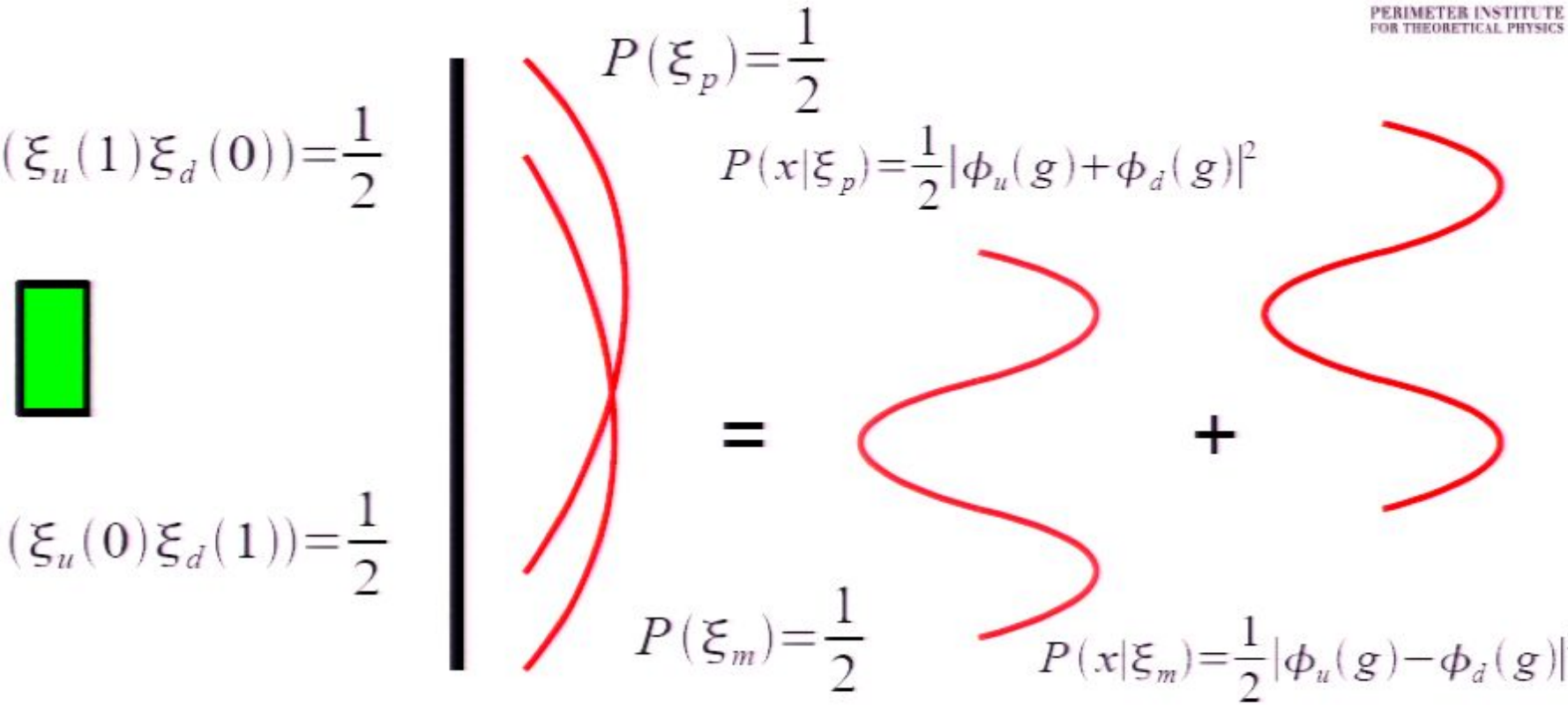
$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0) + \phi_d(g)\xi_u(0)\xi_d(1)\right) = \frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p + \frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry



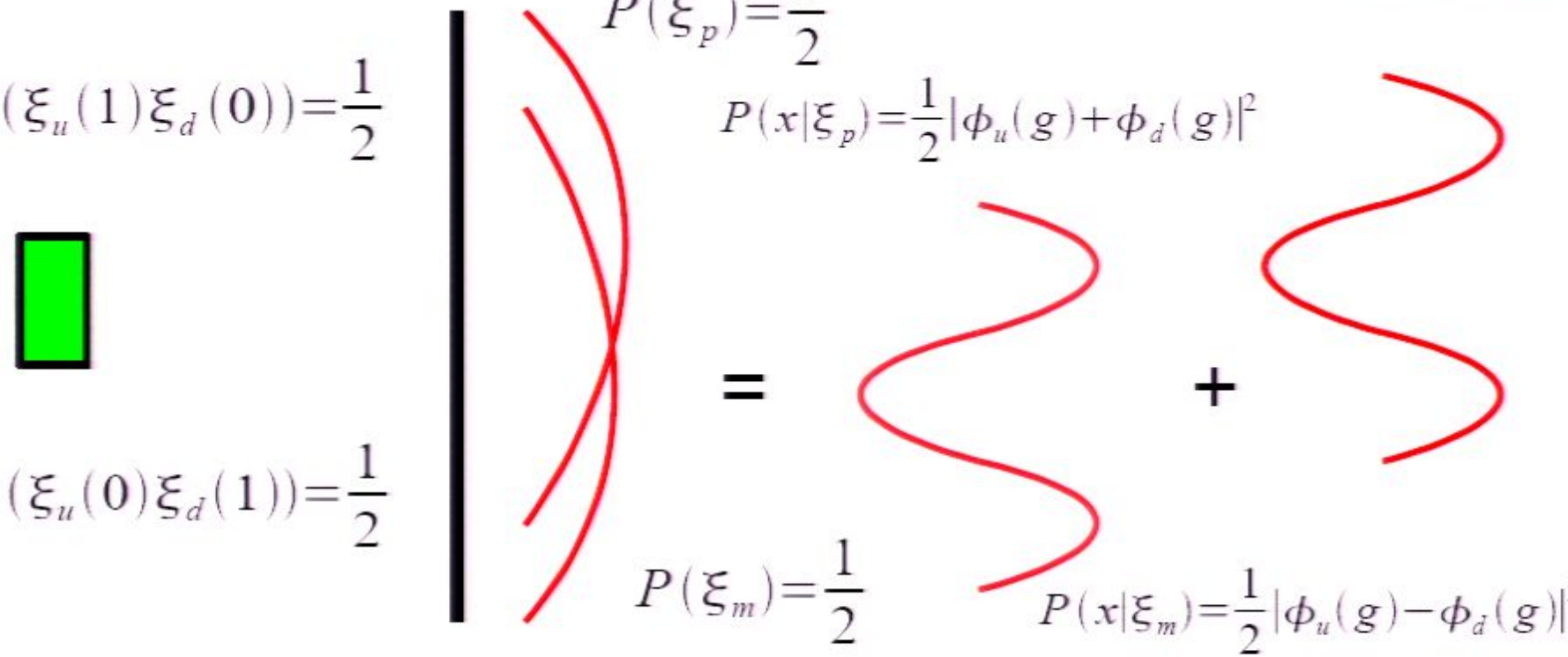
$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)=\frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p+\frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

Quantum phenomena : interferometry



$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)=\frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p+\frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

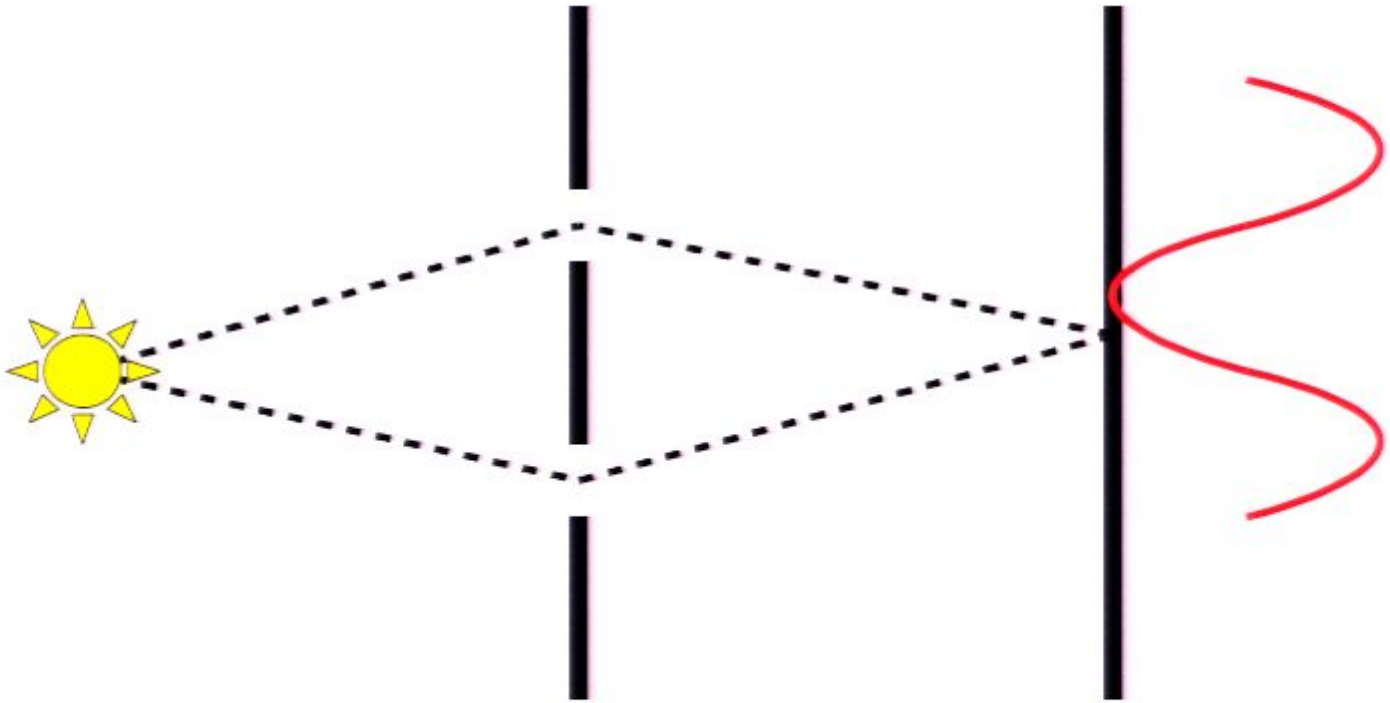
Quantum phenomena : interferometry



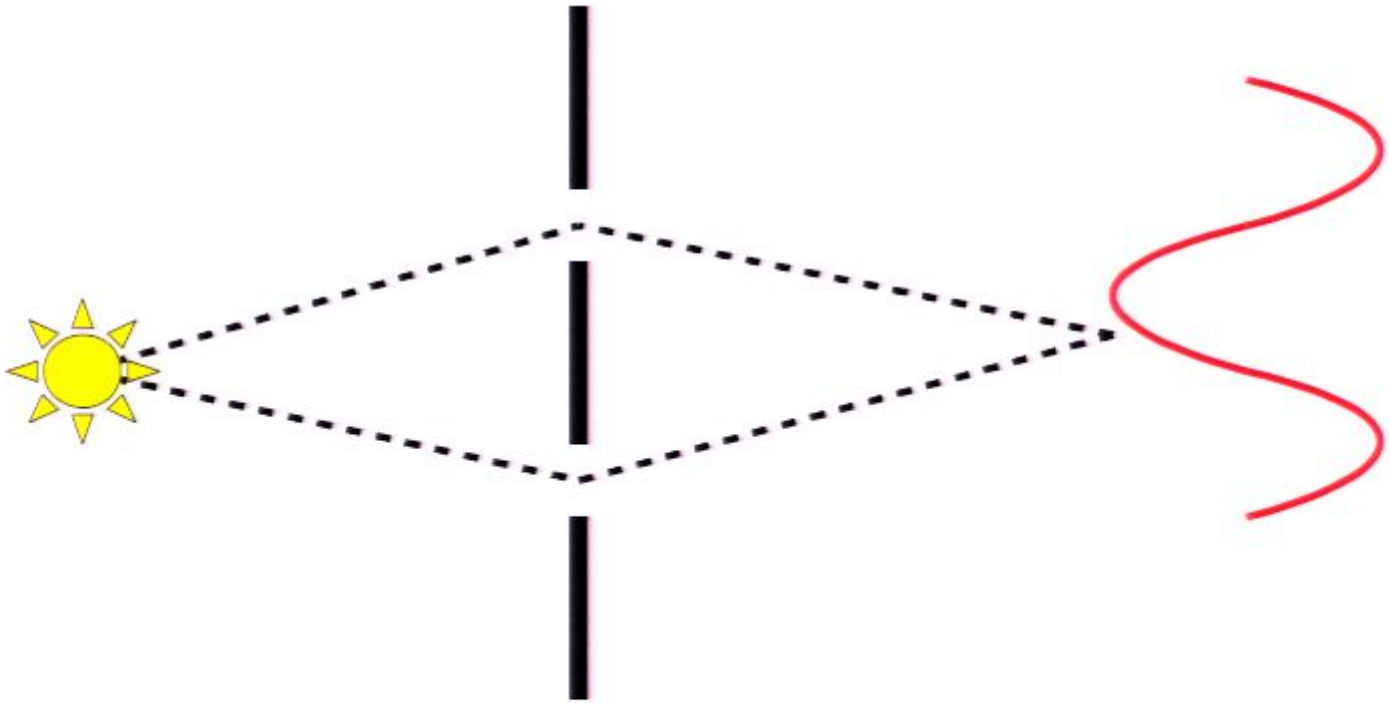
$$\frac{1}{\sqrt{2}}\left(\phi_u(g)\xi_u(1)\xi_d(0)+\phi_d(g)\xi_u(0)\xi_d(1)\right)=\frac{\left(\phi_u(g)+\phi_d(g)\right)}{2}\xi_p+\frac{\left(\phi_u(g)-\phi_d(g)\right)}{2}\xi_m$$

$$P(x|10)P(10)+P(x|01)P(01)=P(x|\xi_p)P(\xi_p)+P(x|\xi_m)P(\xi_m)$$

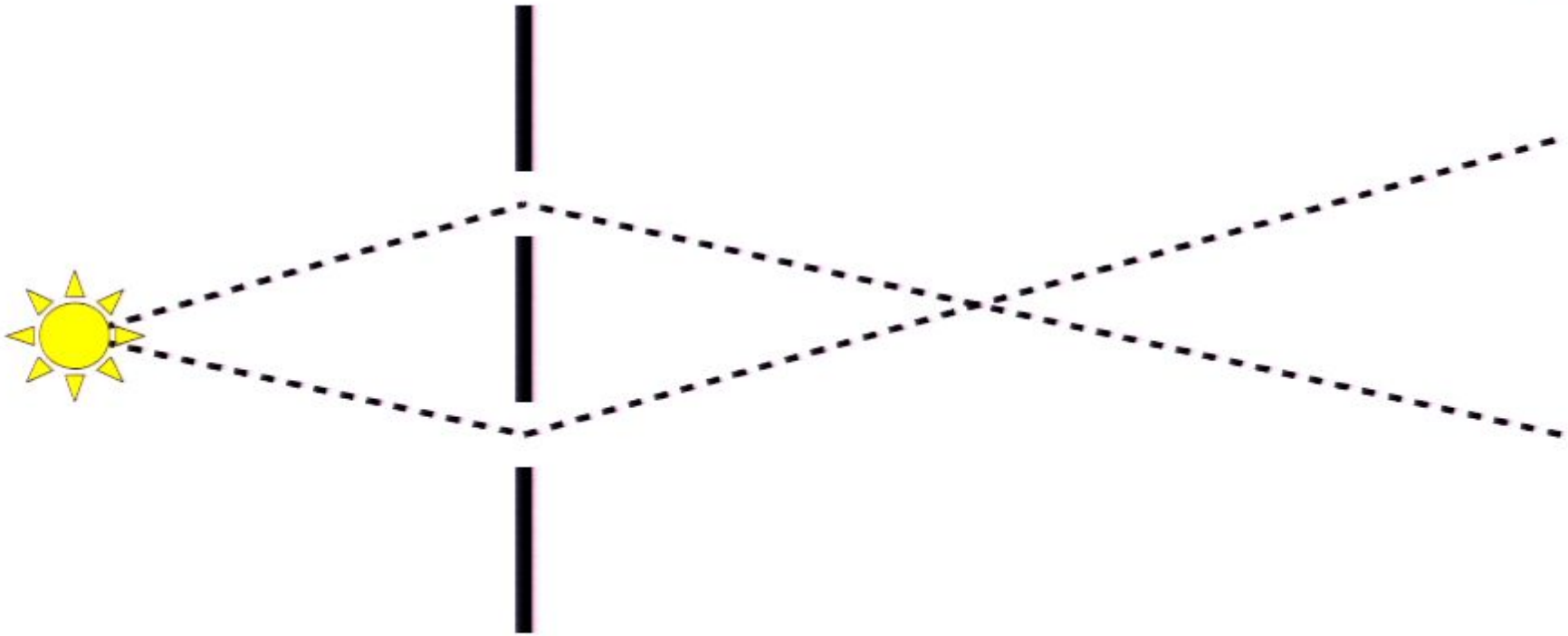
Quantum phenomena : interferometry



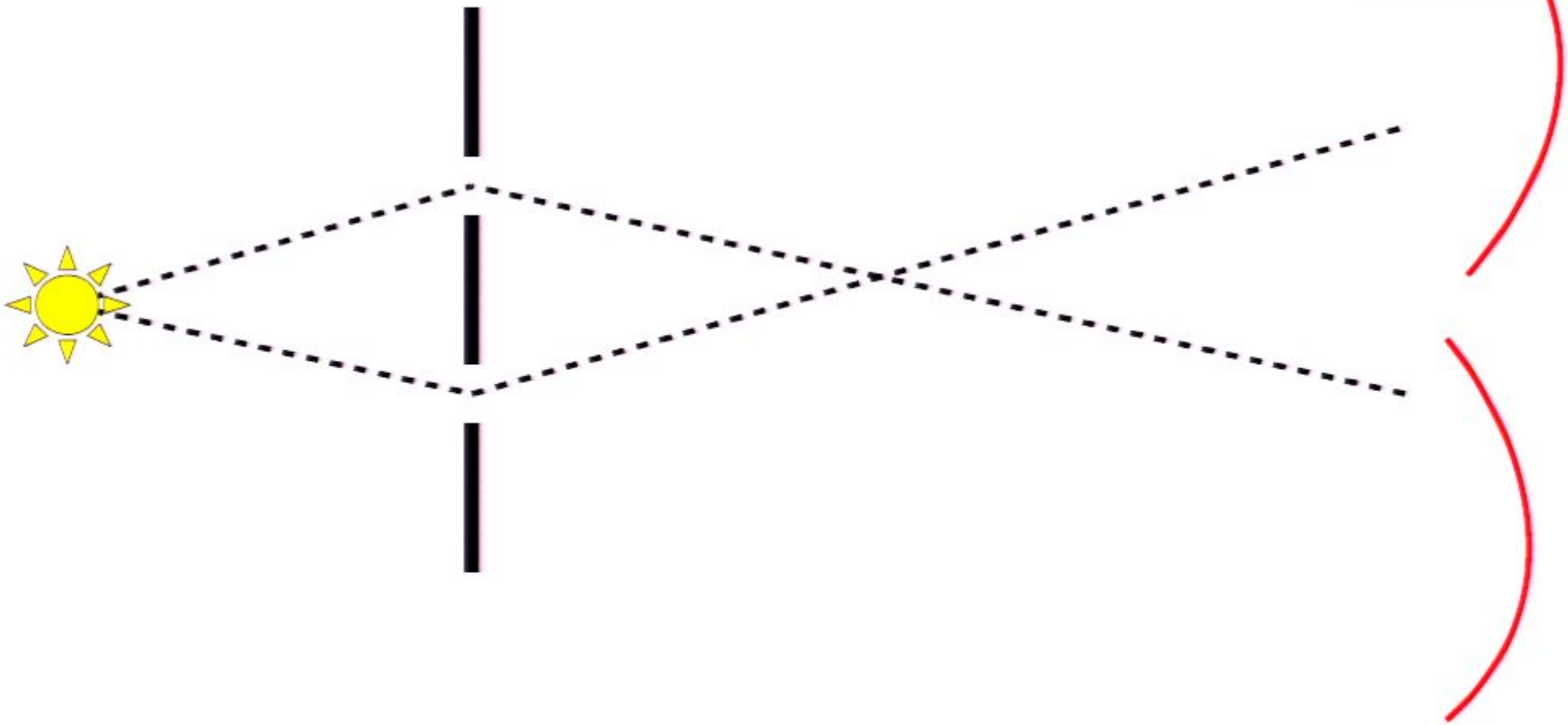
Quantum phenomena : interferometry



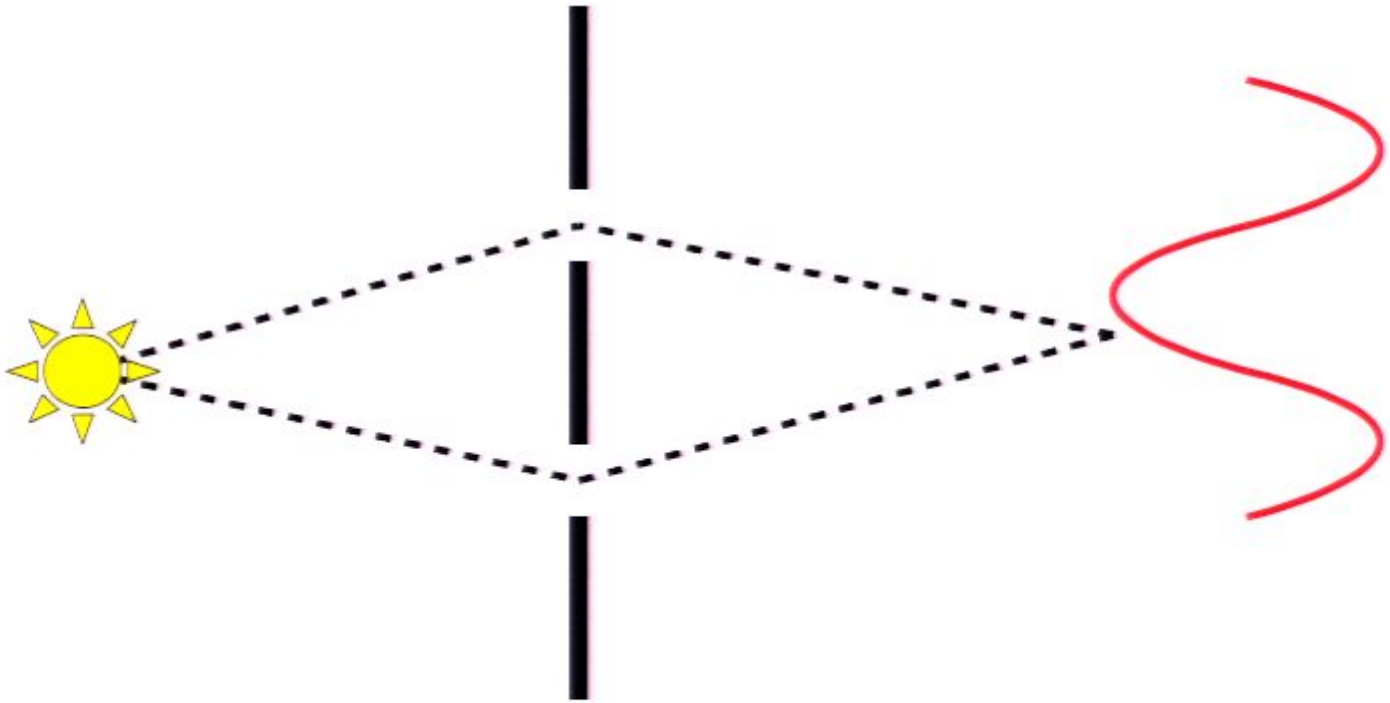
Quantum phenomena : interferometry



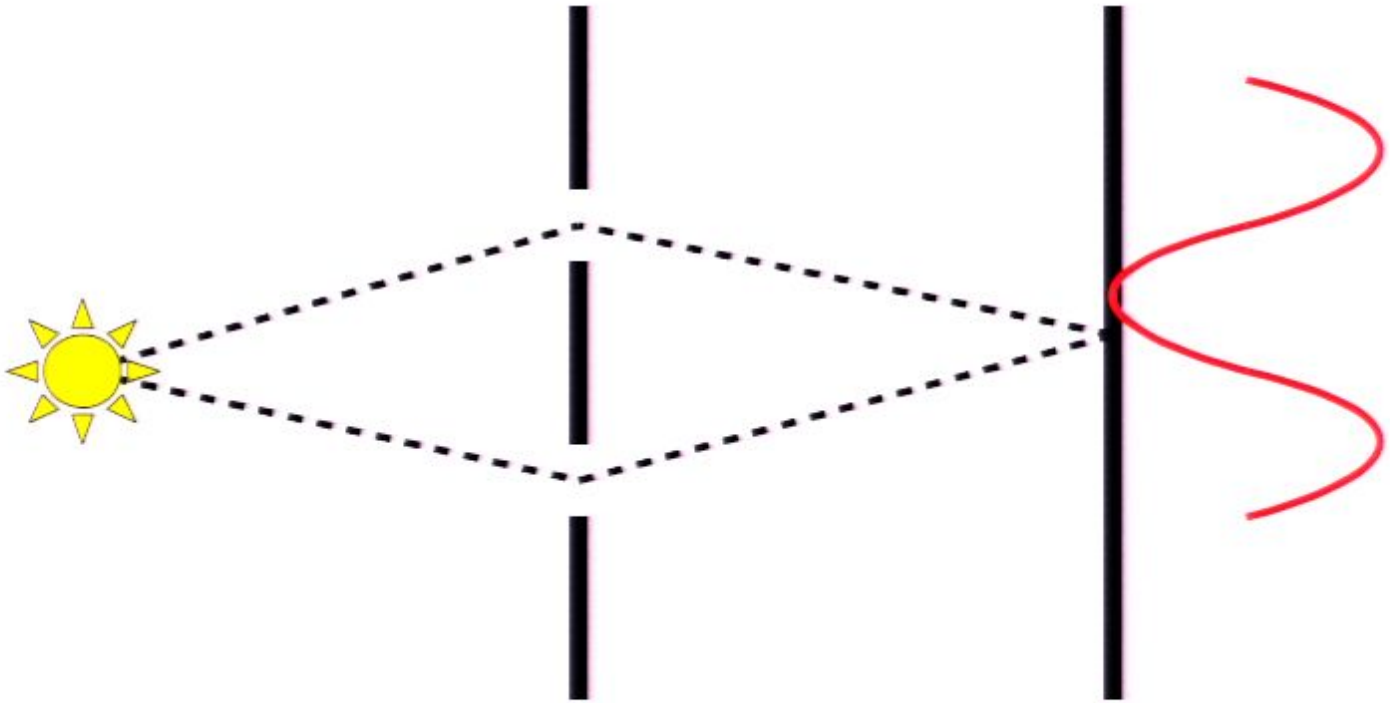
Quantum phenomena : interferometry



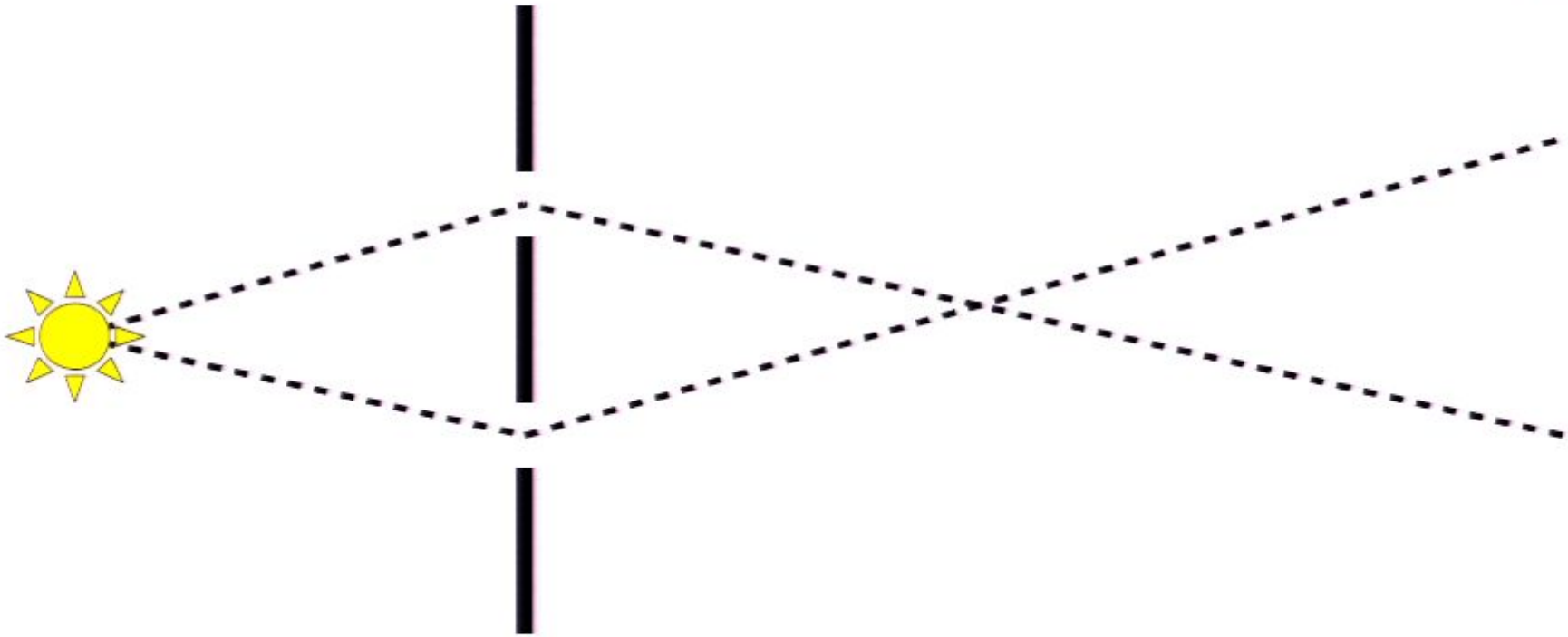
Quantum phenomena : interferometry



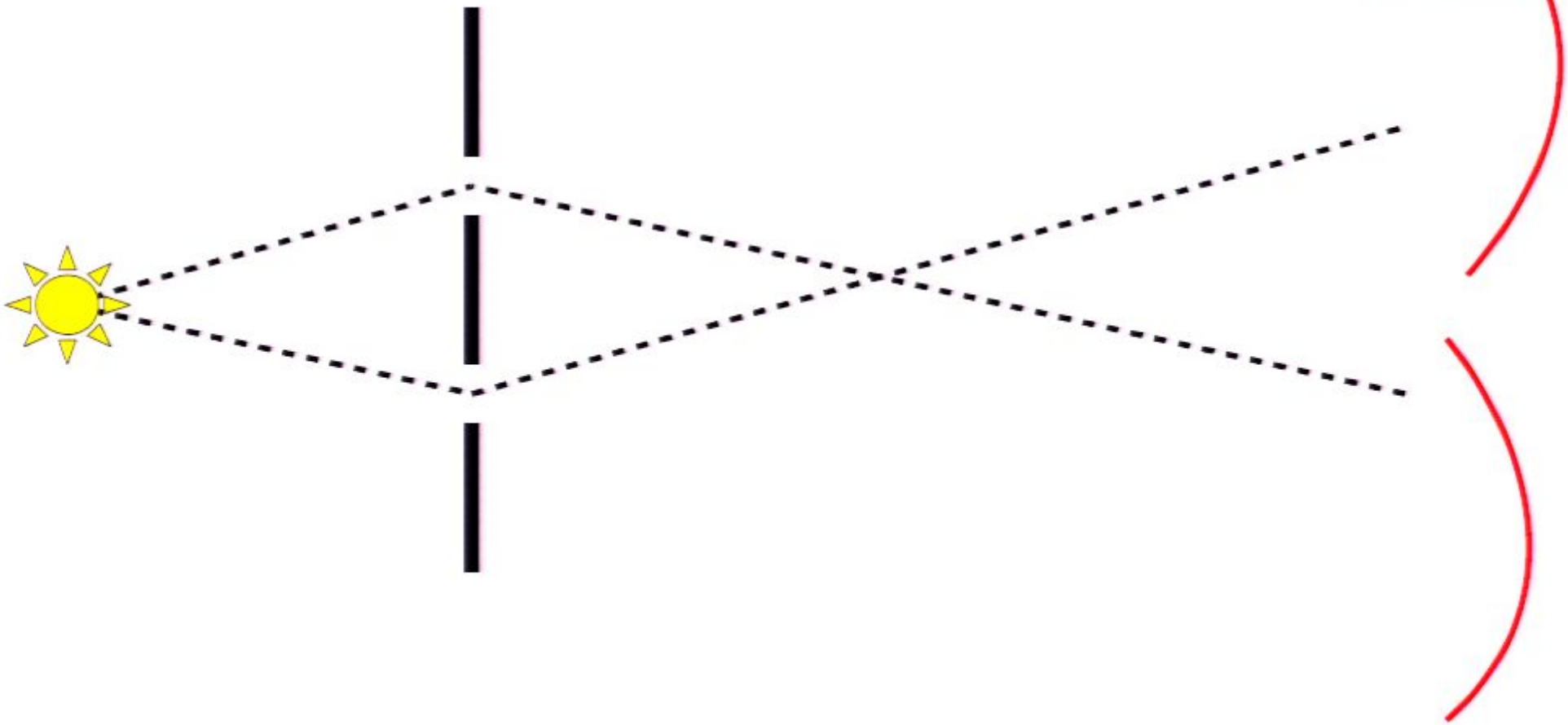
Quantum phenomena : interferometry



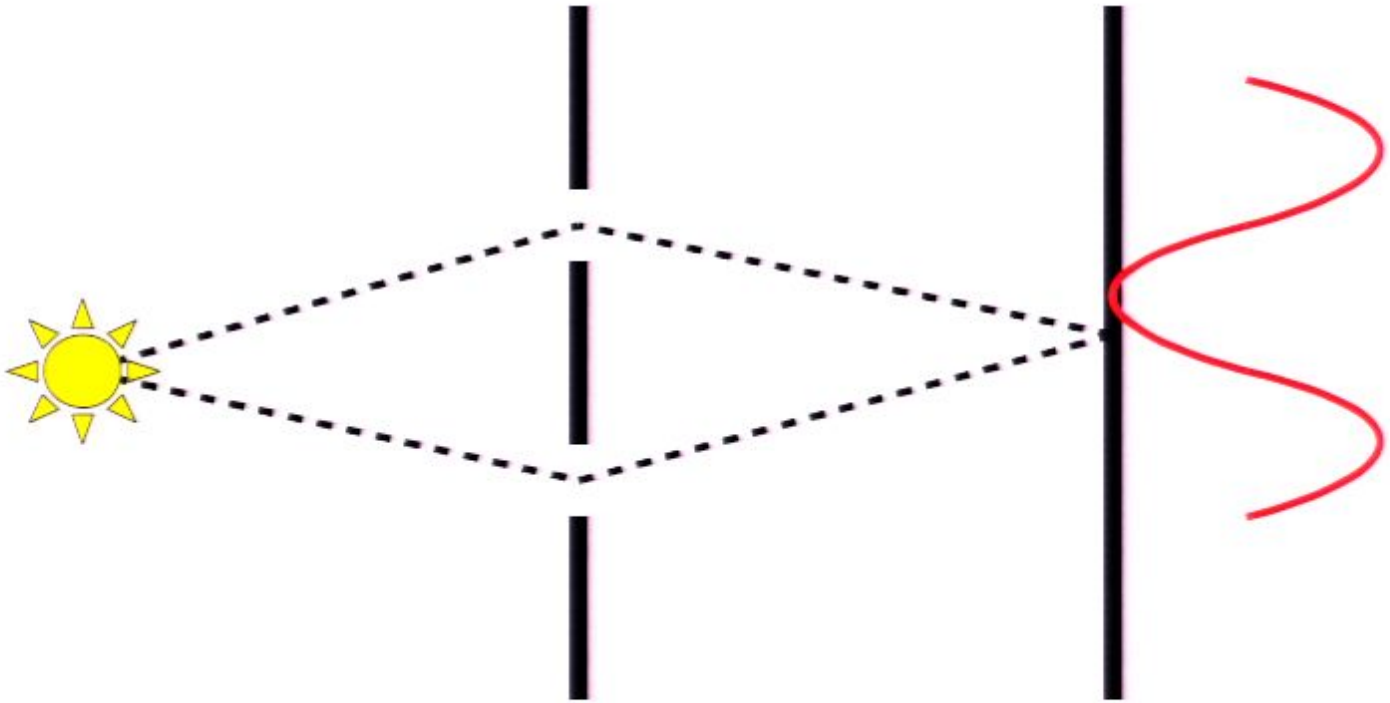
Quantum phenomena : interferometry



Quantum phenomena : interferometry

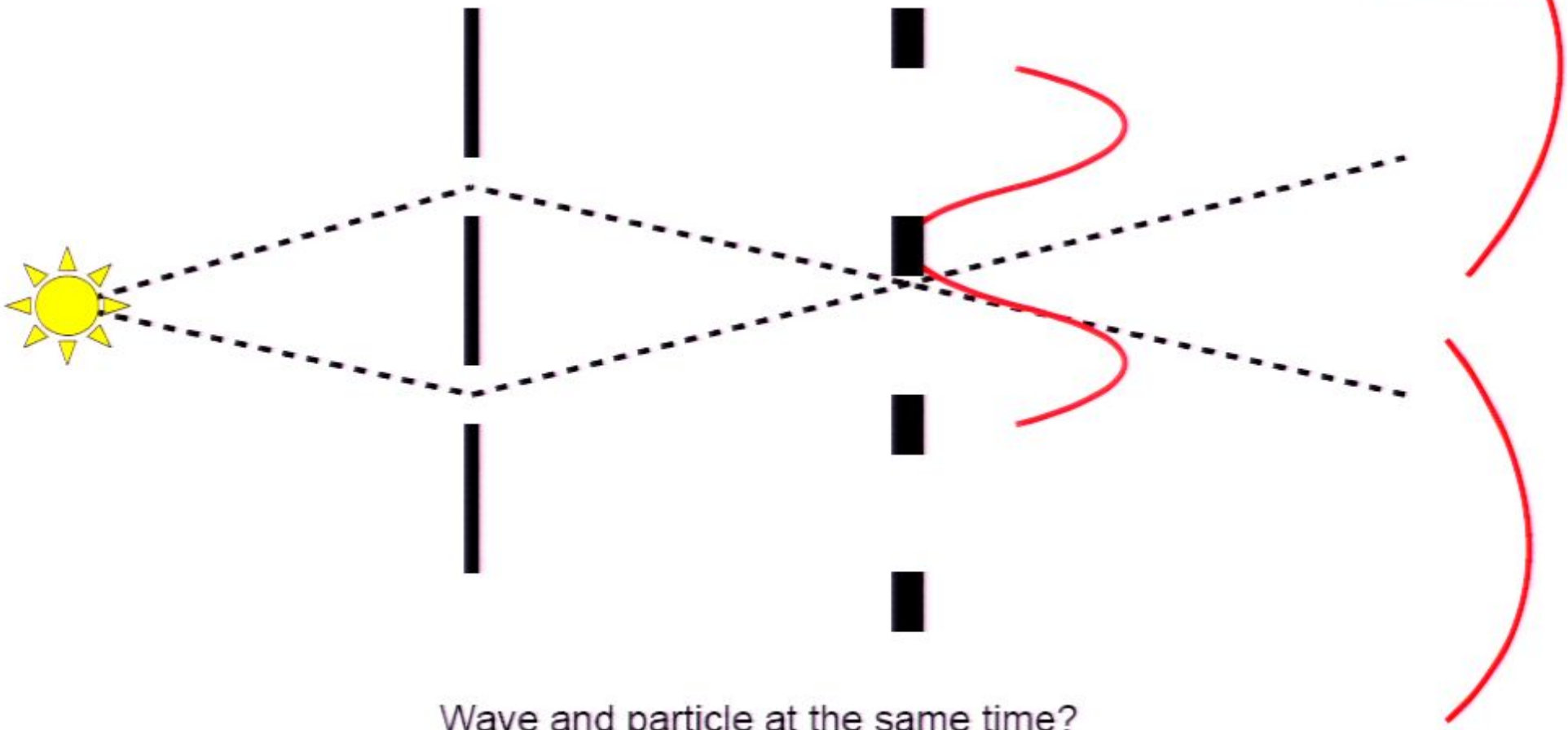


Quantum phenomena : interferometry



Delayed choice as to whether the quanta is a particle or wave?
No phenomena is a phenomena until it is an observed phenomena

Quantum phenomena : interferometry



Wave and particle at the same time?

Quantum phenomena : summary

- A superposition state cannot be simply understood as a statistical mixture of states
  - "Find at x" is just not the same as "Be at x"
- The observed phenomena depends upon the apparatus used to observe it.
  - But the choice of what the apparatus is can be delayed until after the phenomena has occurred?
  - When *is* the choice made?

"It would seem that the theory is exclusively concerned with the 'results of measurement' and has nothing to say about anything else. When the 'system' in question is the whole world where is the 'measurer' to be found? Inside, rather than outside, presumably. What exactly qualifies some subsystems to play this role? Was the world wave function waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer for some more highly qualified measurer -with a PhD?"

J. S. Bell "Quantum Mechanics for Cosmologists"

Quantum phenomena : interferometry